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Historical review of the geological cartography in Ecuador.

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ABSTRACT

Since 1892, seven versions of the national geological map of the Republic of the Ecuador have been published. In 1892, Dr. Theodor Wolf, of the German Scientific Mission, published the 1st map which included a preliminary geomorphological description. Later, Dr. Walther Sauer with the support of the *Universidad Central del Ecuador (*Central University of Ecuador), published a 2nd version in 1950, and then an update in 1970, both included oil wells information. In 1969, the *Servicio Nacional de Geología y Minería del Ecuador (National Service of Geology and Mining of Ecuador)*, and Institut Français du Pétrole (French Petroleum Institute), published the 3rd version which included a mineralogical index. The 4th version was developed by the *Dirección General de Geología y Minas del Ecuador (General Directorate of Geology and Mines of Ecuador)* and Institute of Geological Sciences & Natural Environment Research Council, and was published in 1982, it included a geological model from a plate tectonics approach. Later, in 1993, the *Corporación de Desarrollo e Investigación Geológico Minero y Metalúrgica del Ecuador (Geological, Mining and Metallurgical Research and Development Corporation of Ecuador)* and the British Geological Survey published a 5th version, which included an overview of mineral occurrences on the Ecuadorian Andes. On the 21st. century, in 2001 was published the 6th version, that consisted of a reviewed national geological map, which included data transferring to the geographical information system ArcGis. Ultimately in 2017, the *Instituto Nacional de Investigación Geológico Minero Metalúrgico (National Institute of Geological-Mineral-Metallurgical Research)*, published the 7th version, incorporating the last updated geological results of previous campaigns. Every version contributed to the understanding of the regional geodynamic framework. Nevertheless, in the last two decades, informal coding of units for the geological cartography, thrived, involving a lack of characterization and descriptions of representative outcrops, along with uncertainties on geochronological control for newly mappable defined units, reduce reliability on the national geological cartography, increasing the uncertainties for the understanding the regional geodynamic framework.

Keywords: *Geological Map, Ecuador, History*

Breve reseña historica de la cartografia geologica en Ecuador.

RESUMEN

Desde 1892, siete versiones del mapa geológico de la Republica del Ecuador fueron publicadas. En 1892, el Dr. Theodor Wolf de la Misión Científica Alemana publico la primera versión, incluyendo una descripción geomorfológica preliminar. Luego el Dr. Walther Sauer impulsado por la Universidad Central del Ecuador público en 1950 la segunda versión del mapa con una actualización en 1970, en estas versiones se incluyeron información de pozos petroleros. En 1969, el Servicio Nacional de Geología y Minería del Ecuador y Institut Français du Pétrole publicaron la tercera versión del mapa integrando un índice mineralógico. La cuarta versión del mapa fue elaborada por la Dirección General de Geología y Minas del Ecuador con asistencia del Instituto of Geological Sciences y Natural Environment Research Council y publicada en 1982, proponiendo un modelo de evolución geológica en el marco de la tectónica de placas. Después en 1993, la Corporación de Desarrollo e Investigación Geológico Minero y Metalúrgica y British Geological Survey publicaron la quinta versión, en el cual se incluyó un estudio de prospectos minerales en los Andes ecuatorianos. En 2001, la Dirección Nacional de Geología publico una actualización del mapa, en la cual, destacó la migración de datos al sistema ArcGis. Finalmente, en 2017, Instituto Nacional de Investigación Geológico Minero Metalúrgico, publico la séptima versión del mapa geológico de la República del Ecuador que integra los resultados de todas las campañas geológicas anteriores. Cada una de estas versiones reporto datos que contribuyeron al entendimiento del marco geodinámico regional. Sin embargo, en las últimas dos décadas, la proliferación de unidades informales en la cartografía geológica, vinculada a la ausencia de descripciones y caracterización de afloramientos tipo y control geocronológico de unidades cartografiables definidas de manera inédita reduce la confiabilidad de la cartografía geológica en Ecuador e incrementa la incertidumbre en el marco geodinámico regional.

Palabras claves: Mapa Geológico, Ecuador, Historia

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INTRODUCTION

The Ecuadorian continental margin is located parallel to a subduction zone, where the aseismic submarine Carnegie Ridge is subducted beneath the South American plate (Nocquet *et al.,* 2017; Baize *et al.,* 2020). The high seismicity and active volcanism in the continental margin are superficial expressions of this subduction process (Champenois *et al.,* 2017; Lynner *et al.,* 2020). The Andean population along history have adapted to such natural phenomena. On ancient times, the empirical knowledge of rock types and relief, allowed the development of major infrastructure for the progress of pre-colonial communities (Periferakis, 2019a). The recognition of soil types and drainage patterns allowed agriculture development (Ochoa-Tocachi *et al.,* 2019). The gold and silver appearance on archaeological artifacts implies that pre-colonial communities developed an empirical knowledge on mineral identification (Periferakis, 2019b; Sweitzer, 2020). From the colony to the present date, exploration of mineral resources as: gold, silver, copper carbon, oil, different varieties of salts, and construction material, compelled governments to develop policies for the administration of natural resources (Carrión-Mero *et al.,* 2020). The documentation of natural phenomena like earthquakes, volcanic eruptions, droughts, forced societies to develop land use planning (Armijos *et al.,* 2017: Costa *et al.,* 2020). It is so that empirical and scientific geological knowledge of the relief in which we inhabit, contributes to social resilience against adverse natural phenomena.

Geological research and the geological map

Nowadays, there exist two perspectives on scientific research on geology: 1) the qualitative, that encompasses those methodologies related to the description of physical characteristics of the rocks, using human senses and with the aid of instrumentation (Whitmeyer and Dordevic, 2021). While the quantitative approach, refers to the methods by which both physical and chemical characteristics of the rocks are determined, with the use of standardized measurement units, producing measurable data which allow the construction of mathematical models, such aimed to the explanation of natural phenomena, as tectonic processes among others (Karpatne *et al.,* 2018).

The geological cartography integrates both research methodologies, quantitative and qualitative, displaying the chronological order, the spatial distribution of lithologies and terrigenous non-consolidated material, from a same source, as well as the main morphological and structural features of the relief (Terpock and Biscke, 2002; Whitmeyer *et al*., 2010; Lisle *et al.,* 2011; Spencer, 2017), also, the rocks of a same source and same age are grouped on geological units (Vai, 2001; Duffy *et al.,* 2006; Riccardi, 2011). The geochronological order in which are organized the different represented units, allow to evaluate the regional geological evolution model, namely, a geological map contributes to the understanding of the evolution of the planet (Spencer, 2017).

This representation has been traditionally projected on a topographic map, however in the last decade it was common to find tridimensional representations (Whitmeyer *et al.,* 2010). The geological cartography included the interpretation of the geometry of structures and arrangement of substratum (Spencer, 2017). The scale is a determinant factor to consider, as it indicates the relation among the real relief dimensions and those represented in the topographic map, which, directly influences on the scope and research methodology (Lisle, 2011). Due to the variations on the scales used and the theoretical and technological advances on research methodologies, the geological cartography must be constantly updated (Tziavou *et al.,* 2018). Geological maps are determiners in decision making for the administration of natural resources, in land planning, and risk and disaster management (Barenes and Lisle, 2013; Loughlin *et al.,* 2015; Kimerling *et al.,* 2016).

History of the Geological Map of the Republic of Ecuador.

The table 1 presents the summary of the different version of the geological map, published between 1892 and 2017, whose are described hereunder:

Table 1. ***Geological maps of the Republic of Ecuador***

Title	Author
Geological Map of the Republic of Ecuador, scale 1: 2,000,000, 1892 version.	Dr Theodor Wolf Published by the Geographical Institute of Ecuador H. Wagner & E. Debes in Leipzing
Geological Map of the Republic of Ecuador, scale 1: 1,500,000, 1950 version	Dr. Walther Sauer Published by the *Universidad Central del Ecuador (Central University of Ecuador)* in collaboration with Ministry of Economy of Ecuador and the *Dirección General de Minas (General Directorate of Mines)*
Geological Map of the Republic of Ecuador, scale 1:1,000,000, 1969 version.	Published by the *Servicio Nacional de Geología y Minería* SNGM *(National Geology and Mining Service).* and *Institute Francés del Petróleo* IFP *(French Petroleum Institute)*
National Geological Map of the Republic of Ecuador, scale 1:1,000,000, 1982 version.	Published by the *Dirección General de Geología y Minas* DGGM *(General Directorate of Geology and Mines).* and Institute of Geological Sciences NERC
Geological Map of the Republic of Ecuador, scale 1:1,000,000, 1993 version.	Published by the *Corporación de Desarrollo e Investigación Geológico Minero y Metalúrgica* CODIGEM *(Geological, Mining and Metallurgical Research and Development Corporation*) and British Geological Survey - BGS
Geological Map of the Republic of Ecuador, scale 1:1,000,000, version 2001.	*Dirección Nacional de Geología* DINAGE (*National Directorate of Geology)*
Geological Map of the Republic of Ecuador, scale 1:1,000,000, 2017 version	Published by the *Instituto Nacional de Investigación Geológico Minero Metalúrgico* INIGEMM *(National Institute of Geological-Mineral-Metallurgical Research*)

Dr. Theodor Wolf, the German scientific mission and the Geological Map of the Republic of Ecuador, scale 1:2 000 000, 1892 version

The first version of the geological map of Ecuador (Figure 1) was prepared on the XIX century, between 1868 and 1892. This was initially tasked to the Universidad Politécnica (Polytechnic University), in cooperation with the German Scientific Mission for the Development of the Americas (MCA) (Wolf, 1879). Dr. Theodor Wolf acting as "Ecuador State Geologist", conducted the project with technical assistance of W. Reiss and A. Stübel of the MCA (Sevilla et al., 2021). The result of this project was published in September 1892, in a scientific work named "*Geography and Geology of Ecuador*", which included the "Geological map of the Republic of Ecuador" scale 1:2 000 000 (Figure 1) (Wolf, 1892; Sevilla *et al.,* 2021;

Restrepo-Morantes, 2022). The publication of this map ends the Initial Period (?-1892) of Vera (2016) characterized by the accumulation of knowledge of mine exploration since ancient times and the expeditions of famous naturalists (First French Mission, Charles Darwin, Alexander von Humboldt, etc.)

Figure 1. Geological Chart of the Republic of Ecuador, scale 1:2 000 000, 1892 version. (Wolf, 1892)

Dr. Walther Sauer, Shell Company and the Geological Map of the Republic of Ecuador, scale 1: 1 500 000, 1950 and 1970 versions.

From 1911 to 1928, the Leonard Exploration Company, performed the first geophysical campaigns and exploratory drillings in Ecuador (Guillén, 2021). Between 1930 and 1950, Anglo Ecuadorian Oilfields Ltd., International Petroleum of Ecuador Company, and Shell Company of Ecuador, published lithostratigraphic and biostratigraphic reports, that allowed the definition of lithostratigraphic units in Ecuador (Sauer, 1965; Rivadeneira, 2004). In 1948, Shell Company of Ecuador drove the first chronostratigraphic proposal for the Ecuadorian continental margin, which was included on the geological map of South America, published by the Geological Society of North America (GSNA) (Jenks, 1956; Alvarez Marcillo, 2020). In 1940, the Ministry of Economy of Ecuador, established the *Dirección General de Minas* DGM *(General Directorate of Mines)*. The second version of the Geological Map of Ecuador was developed and published by Dr. Walther Sauer, geology professor at the *Universidad Central del Ecuador* UCE (*Central University of Ecuador*), with the technical cooperation of R. Liddle and A. Stüebi of the American Mining Company, and J. Sotomayor of the *Instituto Geográfico Militar* IGM (*Military Geographic Institute*) (Figure 2) (Sauer, 1965). In 1958, the GSNA, included the information of the 1950 Geological Map of the Republic of Ecuador, scale 1: 1 500 000, in the revision of the Geological Map of South America (Jenks, 1956; Flint, 1967). In 1971, Dr. Walther Sauer, published a second version of the map on the memories of the German Scientific Society (Sauer, 1971).

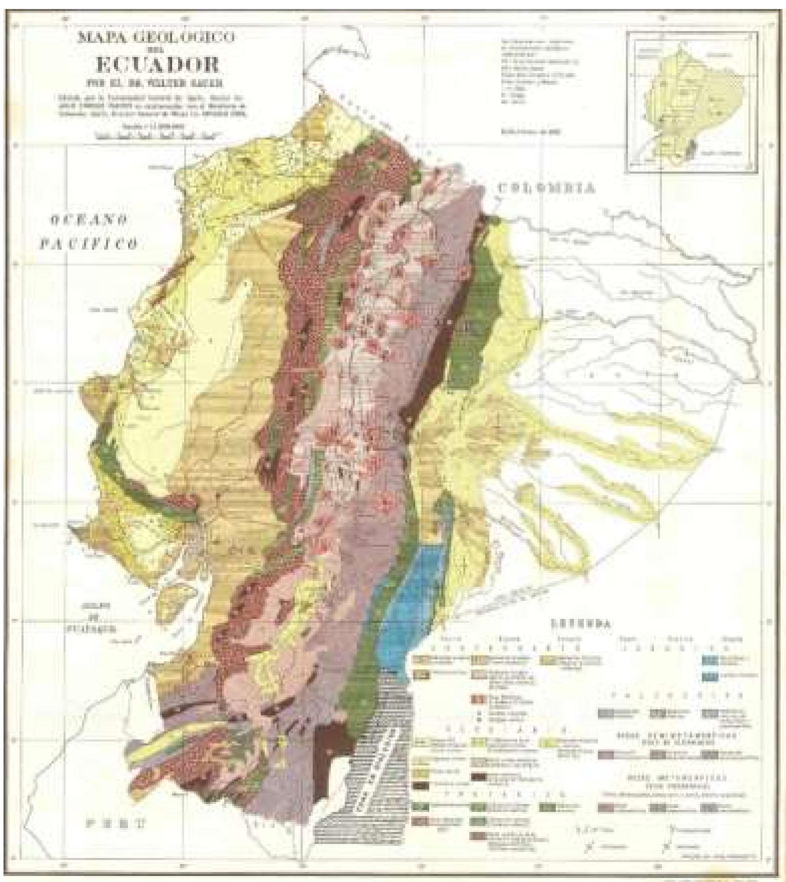

Figure 2. Geological Map of the Republic of Ecuador, scale 1: 1 500 000, 1950 version. (Sauer, 1950)

The Servicio Nacional de Geología y Minería (National Geology and Mining Service), the French Institute for Petroleum, and the Geological Map of the Republic of Ecuador, scale 1:1 000 000, 1969 version.

Between 1958 and 1968, the *Companía de Minas y Petróleos del Ecuador* C.M.P.E (*Mining and Petroleum Company of Ecuador*) and the Consortium Texaco Gulf Co., performed geophysical prospective campaigns in the Oriente basin, with the use of electrical and seismic methods (Alvarez Marcillo, 2020). The reported information enabled the identification of sedimentary sequences limits, and to formally defined the lithostratigraphic units of the Oriente basin (Rassmuss, 1966). From 1960 to 1965, the United Nations drove the "Southern Nations Development Program", on which the Belgian Mining Company (BMC) and North American Mining Association (NAMA), performed the first geochemical campaigns and geochronological studies in the Ecuadorian Andes (Premoli, 1983; Gemuts *et al.,* 1992). In 1960, the Ministry of Industry and Commerce of Ecuador, established the Servicio Nacional de Geología y Minería SNGM *(National Geology and Mining Service)* whose objective was to update the geological map of Ecuador. In this project, the technical assistance was provided by the *Instituto Geográfico Militar* IGM (*Military Geographic Institute*) and the Institut Français du Pétrole IFP (French Petroleum Institute). In 1969, the SNGM published the 3rd version of the map at a scale 1:1 000 000 (Figure 3), in which by the first time were included geochemical sampling points and location of seismic lines (SNGM, 1969).

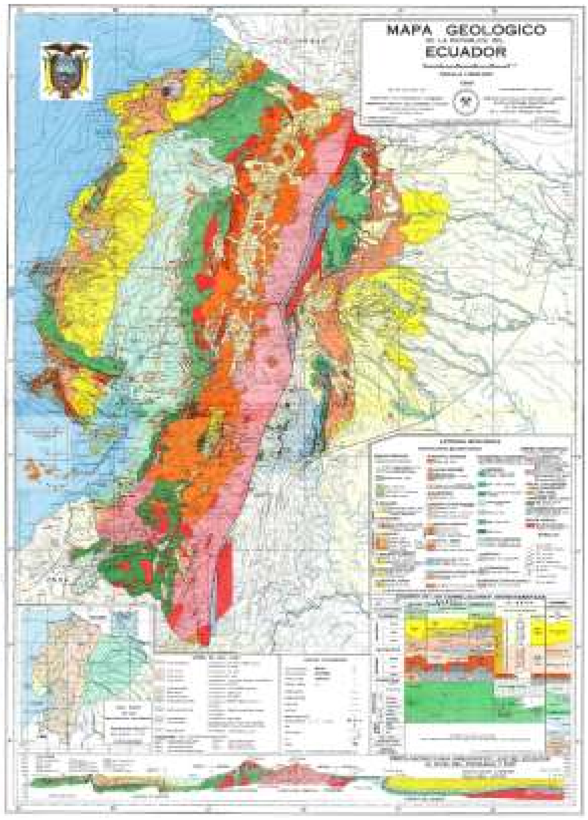

Figure 3. Geological Map of the Republic of Ecuador, scale 1:1 000 000, 1969 version. (S.N.G.M. and IFP, 1969)

Both the Sauer (1950) and the 1969 map would be within the Development Period (1893-1965) of Vera (2016), in which the influence of the mining and oil industry is highlighted. Although that of 1969 would be located in the following period, much of the knowledge contained therein would be that of the previous.

The Dirección General de Geología y Minas (General Directorate of Geology and Mines) and the Geological Map of the Republic of Ecuador, scale 1:1 000 000, 1982 version.

Between 1969 and 1980, the *Comisión Ecuatoriana de Energía Atómica* CEEA (*Ecuadorian Atomic Energy Commission*) , carried out geochemical analyses on intrusive rocks of the Cordillera Real, searching radioactive signatures (CEEA, 1980). Since 1978, the *Centro de Levantamiento Integrados de Recursos Naturales* CLIRSEN (*Integrated Center for Natural Resources Surveys*), interpreted Landsat images bought to Eros Data Center (EDC) of the United States of America, and to the Instituto Nacional de Pesquisas Espaciais INPE (National Institute for Space Research) de Brasil; as well as lateral vision and real aperture radar images (SLAR), acquired by the oil companies of the Amazon region.

In 1981, CLIRSEN conducted aerial photograpy collection of Ecuador, covering 60% and 75% of the Coastal and Sierra regions respectively (CLIRSEN, 1981). In 1982, CLIRSEN and *the Corporación Estatal Petrolera Ecuatoriana* CEPE (Ecuadorian State Petroleum Corporation), presented the 1st aerial radar semi-controlled mosaic of synthetic aperture (SAR).

Between 1975 and 1985, the *Instituto Ecuatoriano de Electrificación* INECEL (*Ecuadorian Institute of Electrification*), performed several feasibility studies for the construction of hydroelectric plants, in which a geological report of interest sites was presented, and K-Ar ages of the igneous rocks were reported (Soto and Taco, 1980). In 1974, the *Instituto Ecuatoriano de Recursos Hidráulicos* INERHI *(Ecuadorian Institute of Hydraulic Resources),* presented an updated version of the "Republic's Fluvial Network", including in their reports lithostratigraphic descriptions concerning the intermontane basins of southern Ecuador (Astudillo and Tobar, 1995). Within the decade of 1970 to 1980 CEPE, Anglo Ecuadorian Oil Company (AEOC) and International Ecuadorian Petroleum Company (IEPC), continued oil exploration campaigns, on which were reported thicknesses, geometry, and geochemical data of the different lithostratigraphic units of the Oriente basin (Alvarez Marcillo, 2020).

Within this context, in 1974, the Ministry of Natural Resources and Energy of Ecuador, established the *Dirección General de Geología y Minas* DGGM *(General Directorate of Geology and Mines)*, whose objective was to develop a new version of the Geological Map of Ecuador (Figure 4). This was done with the advice of the Ireland and the Great Britain governments, through the Institute of Geological Sciences (IGS) and Natural Environment Research Council (NERC).

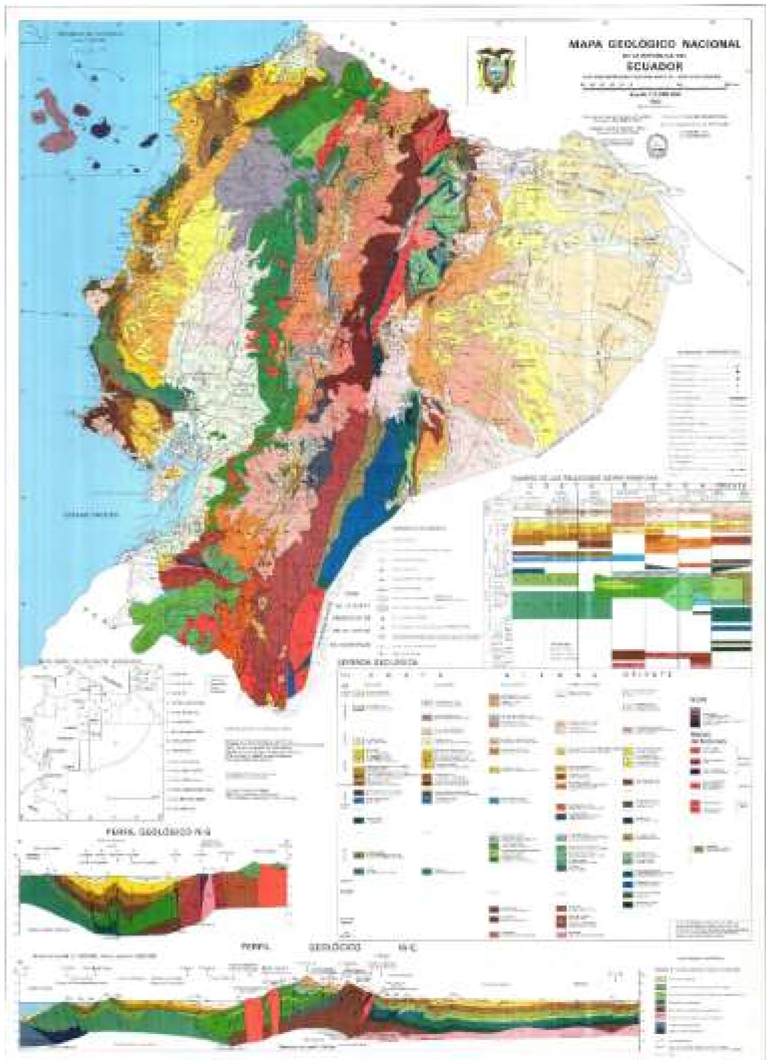

Figure 4. Geological Map of the Republic of Ecuador, scale 1:1 500 000, 1982 version (DGGM. and NERC 1982)

This project involved a mineral research program, and a systematic geological mapping of Western Cordillera of Ecuador. The results were published in 50 color geological maps, scale 1: 100 000 (Kennerley, 1980). Finally, the 1982 Geological Map of the Republic of Ecuador, scale 1:1 000 000, included a new lithostratigraphic proposal sustained in stratigraphic and geochemical information, including new K/Ar ages, in the explained memories "Geología del Ecuador" (Geology of Ecuador) (D.G.G.M., 1982a; Baldock, 1982). Moreover, it was proposed a geological evolution model for the Ecuadorian margin on the plate tectonic framework (D.G.G.M., and NERC, 1982).

The British Geological Survey and the Geological Map of the Republic of Ecuador, scale 1: 1 000 000, 1993 version.

In 1985, the Ministry of Natural and Energy Resources of Ecuador established the Instituto Ecuatoriano de Minería (Ecuadorian Institute of Mining), to update the national geological chart, scale 1: 100 000 (INEMIN, 1985). In 1990, CLIRSEN presented aerial photographs covering 55% of continental Ecuadorian territory (Bravo-Cedeño, 2010). From 1982 to 1985, to the South of the Coastal region, the *Escuela Politécnica del Litoral* ESPOL (*Polytechnic School of the Littoral*), performed geological cartography campaigns in the Guayas and Manabí provinces (Aspden *et al.,* 1990). Similarly, the *Escuela Politécnica Nacional* EPN (*National Polytechnic School*), began with the active volcanoes monitoring (Yepes *et al.,* 1994). International scientific mission of Belgium, Great Britain, Japan, Italy, and France studied the Ecuadorian Andes (Aspend and Litherland, 1992). In 1991, the INEMIN was restructured into the *Corporación de Desarrollo e Investigación Geológico Minero y Metalúrgica* CODIGEM *(Geological, Mining and Metallurgical Research and Development Corporation)* , whom with the technical cooperation of the British Geological Survey (BGS), presented the 1993 Geological Map of the Republic of Ecuador, scale 1: 1 000 000. It was a complement of the tectonic-metallogenic map and constituted the base of the geological and metallic occurrences of the Cordillera Real and Cordillera Occidental. It was designed to a 1:1 000 000 scale, including a geochemical database of the Andes, radiometric dating belonging to 32 intrusive bodies, and a geological evolution model for the Ecuadorian Andes construction (CODIGEM-BGS, 1993). In the Modern Period I (1965-1993) of Vera (2016) geological maps would be published in the years 1970, 1982 and 1993. The most important would be the last two because they would highlight novel knowledge of that time, particularly plate tectonics. .

Figure 5. Geological Map of the Republic of Ecuador, scale 1: 1 000 000, 1993 version (CODIGEM and BGS, 1993)

The Dirección Nacional de Geología (National Directorate of Geology) and the Geological Map of the Republic of Ecuador, scale 1:1 000 000, 2001 version.

From 1996 to 1999, the *Institut de Recherche pour le Développement* IRD (*Research Institute for Development)* and PETROECUADOR, published several scientific articles, where it was summarized the Oriente Basin and Coastal region geology (Rivadeneira, 2004). In the year 2000, the Proyecto de Desarrollo Minero y Control Ambiental PRODEMINCA (Mining Development and Environmental Control Project) developed by CODIGEM, with the BGS technical assistance, published various volumes on the evaluation of mining districts in Ecuador, that included the geology and metallogeny of different mining deposits and districts (PRODEMINCA, 2000). Similarly, scientific missions from Switzerland and the U.S.A., presented results of zircon fission tracks on sedimentary and volcanic rocks belonging to the intramountainous basins (Hungerbühler *et al.,* 2002). At the same time, the *Instituto Geofísico (Geophysical Institute)* (IG-EPN) of the EPN, published results on the monitoring of active volcanoes in Ecuador (Carretier *et al.,* 2022). In 1999, the CODIGEM was restructured into the Dirección Nacional de Geología DINAGE (National Directorate of Geology) entity that compiled and integrated geological information from the years 1994 to 2001, into a new version of the Geological Map of the Republic of Ecuador, scale 1:1 000 000. This version included for the first time, a free access digital database, in addition to the mineral occurrence maps of the Occidental and Real Cordilleras (DINAGE, 2006). This data base was available from the year 2002 to 2016.

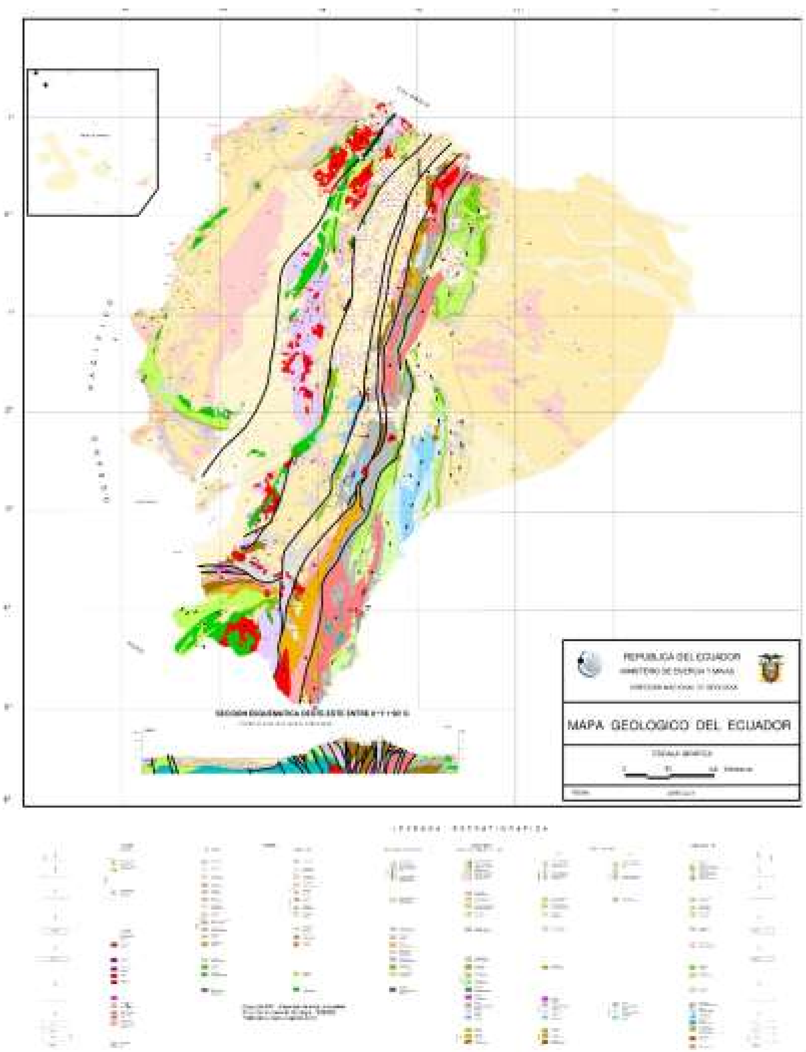

Figure 6. Geological Map of the Republic of Ecuador, scale 1:1 000 000, 2001 version (DINAGE, 2001)

The Instituto Nacional de Investigación Geológico Minero y Metalúrgico, and the Geological Map of the Republic of Ecuador, scale 1:1 000 000, 2017 version

Since 2002 to the present date, the DINAGE, the *Servicio Geológico Nacional* (SGN), the *Instituto Nacional de Investigación Geológico Minero Metalúrgico* (*National Institute of Geological Mining and Metallurgical Research)* and finally the *Instituto de Investigación Geológico y Energético* IIGE (*Geological and Energy Research Institute*), were commissioned the updating of the geological maps scale 1:100 000 on Ecuadorian territory. Parallel, the *Institut de Recherche pour le Développement* IRD (*Research Institute for Development*) and the IG-EPN, mapped and monitored active volcanoes in Ecuador (Carretier *et al.,* 2022). In 2012, the IRD and the EPN published the Geological Map of the Ecuadorian Coastal Margin (Reyes y Michaud, 2012). It is also important to mention that the geological research institutes of Switzerland, U.S.A., Canada, Australia, and Spain, have updated the geodynamic model of the Ecuadorian continental margin (Pratt *et al.,* 2005; Spikings *et al.,* 2015). All this information was integrated on the latest version of the 2017 Geological Map of the Republic of Ecuador, scale 1:1 000 000, which was considered international stratigraphic guidelines and fundamentals, and the application of standardized coding for their cartographic representation.

Is in this context, along the history of the Republic of Ecuador diverse geological research campaigns on a regional scale published different versions of the national geological map at different scales, applying different methodologies and considering different research objectives. This caused a multiplication of informal geological units, increasing uncertainties on the reliability for the regional geological evolution model. The present bibliographic research assembles information belonging to 137 scientific publications relating to regional geology, three stratigraphic lexicons and seven versions of the Geological map of the Republic of Ecuador from 1892 to 2017, aiming to present an assessment on the development and the results concerning the Ecuadorian geological cartography. The maps of 2001 and 2017 are within the Modern Period II (1994-present) of Vera (2016) which stands out for the use of geographic information systems, precision GPS and constant updating of databases.

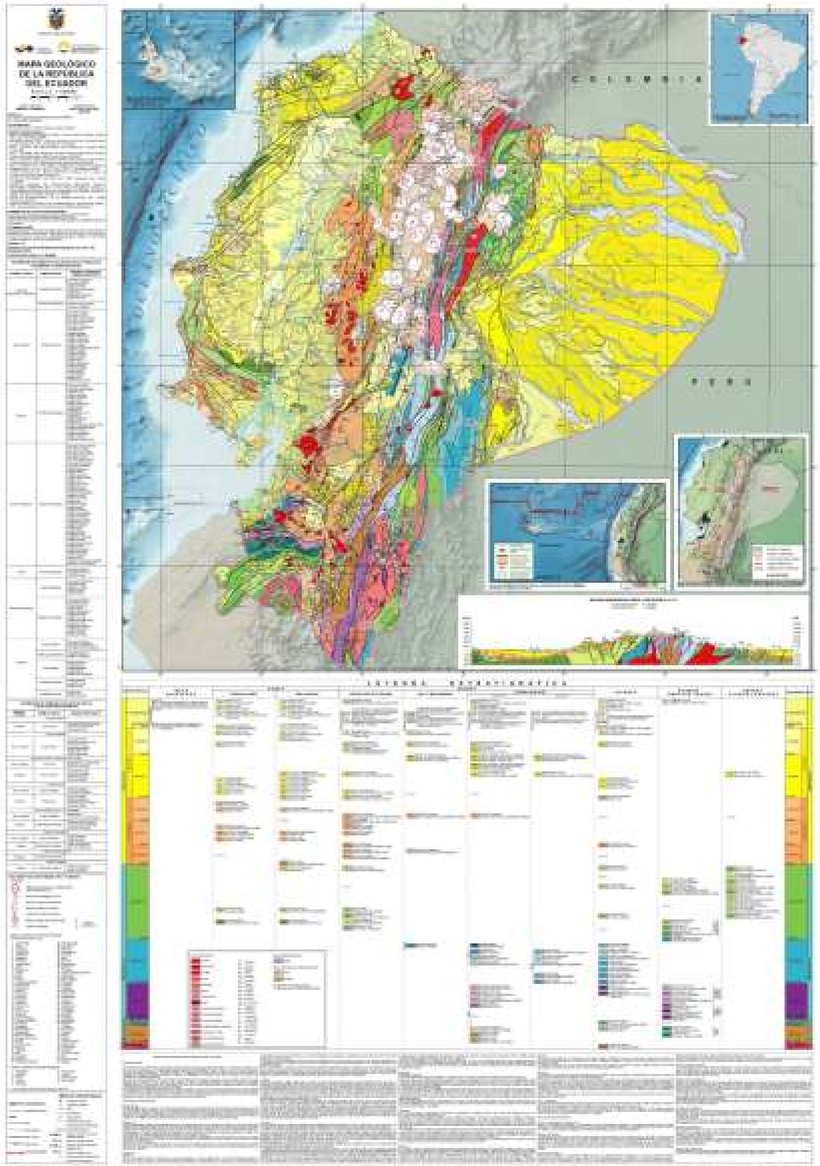

Figure 7. Geological Map of the Republic of Ecuador, scale 1:1 000 000, 2017 version. (INIGEMM, 2017)

METHODOLOGY

The seven versions of the Geological Map of the Republic of Ecuador, from 1892 to 2017, 137 scientific publications, three stratigraphic lexicons, and 77 technical memories, were compiled from the *Centro de Información Geológico Minero y Ambiental* CIGMA (*Mining and Environmental Geological Information Center*), belonging to the IIGE; from the Facultad de Geología y Petróleos (Faculty of Geology and Petroleum) of the EPN; the library of the *Facultad de Ingeniería en Geología, Minas, Petróleos y Ambiental*

FIGEMPA (*Faculty of Engineering in Geology, Mines, Petroleum and Environmental*) of the UCE; the digital repository belonging to the *Facultad de Ingeniería en Ciencias de la Tierra* (*Faculty of Engineering in Earth Sciences*) of the ESPOL; the institutional repository of the *Facultad de Ciencias Naturales (Faculty of Natural Sciences)* of the *Universidad de Guayaquil* UG (*University of Guayaquil*); physical repository of the library of the Casa de la Cultura del Ecuador (House of Culture of Ecuador). The summary table of the considered information on this research, is presented in Supplementary material 1, and was built according to parameters relating to multiple formats, accessibility (relating to free access of information), and scientific valuation (Gómez-Luna *et al.,* 2014; Okoli and Schabram, 2010).

In every version of the geological map, the lithostratigraphic units were considered as the basic units for the geological cartography (Murphy and Salvador, 1999). Furthermore, stratigraphic relations were identified, and the main regional structures mapped were recognized. These observations were made with the objective of identifying inconsistencies, contradictions, and the absence of information.

The analysis of bibliographical data implies transformation of conceptual or theoretical information to a list of finite measurable parameters (Dougherty, 2013). Considering the recommendations of Romei and Ruggieri, (2013), Miles *et al*., (2018) and Herrera-Franco *et al.,* (2020) common parameters were identified in the analyzed bibliographical documents, in this case the version of the geological maps. Then these parameters were evaluated among them. At this point were considered the recommendations of the International Union of Geological Sciences (IUGS) referring to geological cartography were considered (IUGS, 2019). In this manner, the results are presented on data tables and graphics depicting variables, as: 1) coverage area of geological information mapping, 2) lapse of time between publications, number of reported geological units, 3) number of formal geological units, 4) number of informal geological units, and 5) number of reported geological structures.

The coverage area refers to the density of field data obtained and reported in a geological map, this area can serve as a parameter to assess its reliability (Lisle *et al.,* 2011; Spencer, 2017). Even though every version of the Geological Map of the Republic of Ecuador, depicts the country's geology, every version reports a different regional coverage area. The 1969, 1984, 1993 and 2017 versions report the coverage area as square kilometers, whereas the 1892, 1950 and 2001 versions did not report it. On the other hand, it was considered the variation of Ecuador's politic limits regarding to the total geographical area, being the reason by which it was decided to represent this parameter as percentage on basis to the Republic of Ecuador's area. Nowadays, this has a value of 283 560 km^2.

The main evaluated parameter in this work, was the number of reported lithostratigraphic units, which was assessed in function of the IUGS recommendations, for the definition of mapped units in a geological map. Those units that complies with the conventional stablished rules, are considered as formal. While those that were not described in a conventional manner, are considered as informal. Regarding the number of reported geological structures, were considered faults and folds holding a formal name, not being included photo interpreted lineaments. Considering that in a geological map, the lithostratigraphic proposal should be organized according to the international chronostratigraphic table, it was decided to evaluate the number of data that underpin the proposals, so it was included the reported radiometric ages present on the different versions of the geological map were included. Every one of these parameters were evaluated in function of the time passed between the publish of a new version as of the previous one.

On the discussion section, it is compared the methodologies used on every version of the national geological chart, to the IUGS recommendations (IUGS, 2019), and the naming, stratigraphy, symbolization, and abbreviations standards for the Ecuadorian geological mapping (IIGE, 2019), with the purpose of identifying inconsistencies among standards and the studied geological maps, in addition to contribute to the identification of not reported geological research lines, and to propose a common research line for the development of the future national geological cartography.

RESULTS

On table 2, a summary of the obtained data gathered from the analysis of reported bibliographic information is presented. These data allow to quantitatively evaluate the presented results on every version of the Geological Map of the Republic of Ecuador.

Table 2. Summary of the different evaluated parameters of the Geological Map of the Republic of Ecuador.

Parameters	Wolf (1892)	Sauer (1950; 1970)	SNGM. y IFP (1969)	DGGM. y NERC (1982)	CODIGEM y BGS (1993)	DINAGE (2001)	INIGEMM (2017)
Covering área (%)	N.I.	N.I.	11%	27%	60%	S.I.	16%
Time (years)	N.I.	58	19	13	11	8	16
Number of reported geological units	10	31	52	74	117	121	152
Number of formal geological units considering IUGS	0	0	16	52	91	91	91
Number of informal geological units	10	31	36	22	26	26	61
Number of geological structures reported	-	11	16	20	32	32	75

N.I. No information.

In 1892, Dr. Theodor Wolf published the results of 19 geological voyages across Ecuador, achieved in 24 years of research. The structure of the Ecuadorian continental margin relief is explained by ten informal geological units. On the coastal plain it was distinguished four basins: Guayas, Southern Manabí, Northern Manabí, and Esmeraldas. On the Andes, it was discriminated metamorphic rock series of the Cordillera Real, from the volcanic rocks of the Western Cordillera. On the Inter Andean valley, it was reported 17 volcanic edifices. For the Oriente basin, it was described by the first time the Pastaza alluvial cone, and were described the first fossils: ammonites, and bivalves. This research provides the first formal morphological description of the Ecuadorian continental margin (Figure 1).

After 58 years, the 1950 map included information of 42 geological sections, 82 seismic lines, 39 drillings, and the fossil record of the Oriente basin and the coastal region, and 31 geological units of the continental margin, contributing to the definition of stratigraphic floors in Ecuador (Sauer, 1950). Subsequently, it was integrated geochemical data of rock belonging to the Western Cordillera, intrusive ages, and 11 regional geological structures in its final version Sauer, (1971) (Figure 2).

It was made through geological mapping campaigns to scales 1: 1 000 000 and 1: 500 000, mainly in the southern part of the Ecuador and on the coastal region, covering around 31 192 km2, that at the present date represents 11% of the territory (SNGM and IFP, 1969). The IFP included biostratigraphic details and palynological studies, with the purpose of discriminating continental from marine sequences of the Oriente basin. While for the coastal region, seismic studies enabled to evaluate thicknesses of the previously defined macro-sequences. The final version was published after 19 years, and included a regional correlation considering 52 lithostratigraphic units, and 16 regional geological structures (SNGM and IFP, 1969) (Figure 3).

In 13 years the DGGM and NERC included information gathered from geological mapping at scales 1: 500 000, 1:250 000 and 1: 100 000, for the North of the Sierra region and Oriente, covering 76 561 km2 (DGGM., 1982b), representing 27% of the current Ecuador's territory.

This mapping campaign was substantiated in biostratigraphic reports, geochemical data, and K/Ar ages, mainly related to the southern part of the Western Cordillera, due to the mining potential previously reported in the region. This work presented the first description of rock mineralization in the Western Cordillera (Figure 4). This information allowed the description of 74 geological units and 20 regional geologic structures, also it was proposed for the first time, a geologic evolution model within the frame of plate tectonics (Baldock, 1982).

It was developed from the geologic cartography campaigns at scales 1:250 000, 1:100 000 and 1: 50 000, covering 170 136 km2, representing around 60% of the current Ecuadorian territory. During the 11 years of research this campaign took, it was presented the lithostratigraphic detail of the Real and Western Cordilleras, supported with data encompassing: stratigraphic, biostratigraphic, provenance, pluton's and porphyries geochemical characterization, volcanic formations, and geochronological studies including K-Ar, Sm-Nd, Rb-Sr, Re-Os and U-Pb dating systems CODIGEM and BGS (1993). It is also important to remark that in this campaign, it was for the first time considered the "lithotype" concept, from which metamorphic rock series belonging to the Cordillera Real were discriminated, allowing the proposal of a model describing multiple terrain accretions events, in order to explain the structure of the Eastern Cordillera (Litherland et al., 1994). For the first time the data of the national geologic map were integrated to a geographical information system (MapInfo). In this campaign, were discriminated 117 lithostratigraphic units, and 32 regional geological structures (Figure 5).

After 8 years of research, the results published by PRODEMINCA, (2000) were incorporated to CODIGEM and BGS (1993), by DINAGE, (2001). In the historical outlines and methodologies of DINAGE, (2001), there were not reported a specific study area, due to the fact this version of the map was only sustained on a collection of bibliographical data. After 8 years of research, the results published by PRODEMINCA, (2000) were incorporated to CODIGEM and BGS (1993), by DINAGE, (2001). This version of the map focused on mineral deposits. Besides the CODIGEM and BGS (1993) data base was restructured into ArcGIS and AUTOCAD. This bibliographical collection identified 121 lithostratigraphic units and 32 regional structures (Figure 6).

After 16 years, INIGEMM, (2017) included compiled information obtained through geological mapping at scales 1: 100 000 and 1: 50 000, those at the year 2017 covered 45 369 km2, representing 16% of Ecuadorian territorial area. This map was supplemented with the bibliographical compilation of previous versions of the map and reported 152 lithostratigraphic units and 75 regional geological structures (Figure 7). The inherent data base was structured on ArcGis according to the guidelines of the Secretaría Nacional de Planificación y Desarrollo SENPLADES (National Secretariat for Planning and Development) for geoinformation (SENPLADES, 2013). The information of such data base follows the guidelines of the document "Estandarización de abreviación, simbolización y abreviaturas para el cartografiado geológico, versión 1.2" INIGEMM, 2017 (Standardization of abbreviations, symbolization and abbreviations for geologic mapping, version 1.2).

DISCUSSION

From 1892 to 2017, it had been published seven versions of the Geological Map of the Republic of Ecuador. In every version a different methodology was used, having a different objective each time, and considering a different scale. This is reflected on the diversity of presented results on every version. In these results do exist quantifiable parameters as: 1) covering area, 2) number of lithostratigraphic units and 3) regional structures. With the objective of describing the state of the art of the geological cartography of Ecuador, next is assessed the progress of the aforementioned parameters along the time.

Covering area

In the last century, the national boundaries of Ecuador have been modified, and therefore the national territory, and considering that the covering area of every version of the Geological Map of the Republic of Ecuador must be evaluated in function of the same measuring unit, it was decided to evaluate the covering area of each version in terms of percentage, and in function of the current area of the national territory (283 560 km²). On figure 8, it is presented the evolution of the covering area parameter of every geological map along the time.

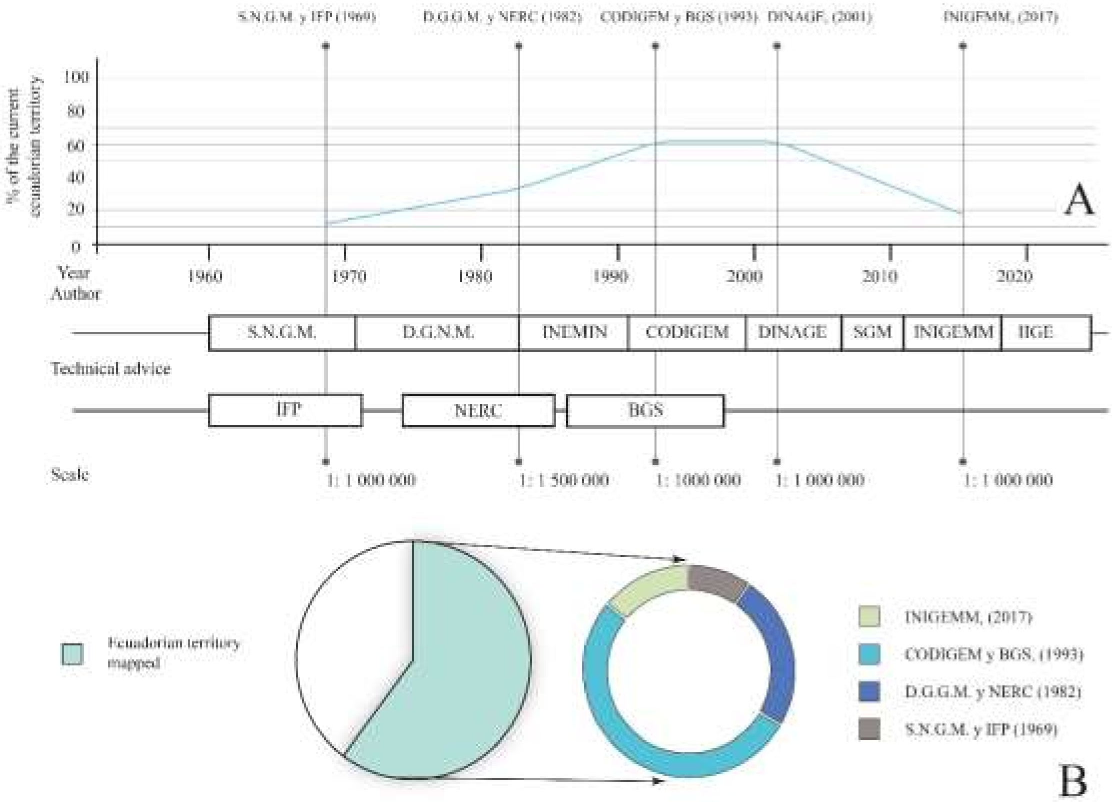

Figure 8. Reported covering area on each geological research campaign. **A**. Time vs current Ecuadorian area (%). **B**. Cumulative diagram of the studied territory. On the lower area of graph A, it is shown the organization on charge for the geological mapping on a national scale, the technical advisor, and the scale of the map.

The methodology used on the versions of Wolf, (1892) and Sauer (1950), indicates that those research works are sustained on voyages descriptions and geological sections, nevertheless, it is not formally reported the study area. On the decade of 1960 to 1970, the research methodology transitioned to geological mapping of topographic maps at scale 1: 100 000, allowing to cover 11% of national territory (SNGM and IFP, 1969). For the 1970-1980 decade, the scale considered was 1: 50 000 and 1:25 000, covering 27% of the territory (D.G.G.M. and NERC, 1982). In the 1980-1990 decade, the objective of both CODIGEM and BGS, (1993) was to evaluate the geological and mineral potential of the Western and Real Cordilleras, for achieving that, the geological mapping covered 60% of the national territory at scales 1:200 000, 1:100 000 and 1: 500 000.

At the beginning of the XXI century, the objective of DINAGE, (2001) was to integrate the data base of PRODEMINCA, (2000) into a new version of the national geological map, preserving the covering area as CODIGEM and BGS, (1993). In the last decade, INIGEMM, (2017), reported partial results of geological mapping campaigns at scales 1:100 000 and 1:50 000, encompassing 16% of the national territory, supplementing the map with bibliographical information.

The time vs covering area (%) diagram, is presented on Figure 8, it can be observed that in the 1980-to-1990-decade CODIGEM and BGS, (1993), increased the covering area compared to the previous geological mapping campaigns. While from 2011 to 2017, the covering area diminished, however, the DINAGE, (2001) and INIGEMM, (2017) versions of the map, sustained their results in bibliographical information. At the present date, only 60% of the national territory has been mapped (Figure 8)

Number of reported lithostratigraphic units

The number of mapped units on every version of the Geological Map of the Republic of Ecuador, are quantifiable, and then assessed among the different versions. In this sense Wolf, (1892) reports 10 units, while Sauer (1950) includes 31, and the SNGM. and IFP, (1969) discriminated 52. Subsequently D.G.G.M. and NERC, (1982) reports 74 units, and CODIGEM and BGS, (1993) included 117, DINAGE, (2001) identifies 121, while INIGEMM, (2017) 152 units.

Figure 12 depicts the relation among the number of reported units on every version of the Geological Map of the Republic of Ecuador, and time. It is seen a regular growing tendency. This implies that every version of the map reported more units than the previous. Furthermore, during the 1980 to 1990 decade (CODIGEM y BGS, 1993), and from 2010 to 2020 (INIGEMM, 2017), the tendency increases compared to the rest. On the other hand, for DINAGE, (2001), is observed a horizontal tendency.

The number of reported units on the different version can be compared to the number of formal and informal units. For this, it is considered the IUGS, (2019) recommendations, regarding to the definition of mappable geological units. For a formal unit, it should be at least described the location and type outcrop characterization, detailed lithostratigraphy, stratigraphic relations, regional correlation, relative age, absolute age, biostratigraphic detail, depositional environment interpretation and a suitable geographical delimitation. This description must be published on scientific media accessible to the public and of continuous publication. While those units considered informal, are such that lacks the mentioned requirements. A geological map must prioritize the cartographic representation of formal units. Informal units will be only used on specific cases and momentarily, or for preliminary studies (Riccardi et al., 2011). If it is compared the number of reported mapped units in function of proposed informal units, from 1950 to 2001, the behavior of both parameters is different (Figure 9). The number of informal units has a lineal behavior with a downward trend, while the number of mapped units maintain a positive slope. In contrast, from 2002 to 2017, both parameters maintain a similar behavior with positive slopes.

If it is compared the number of mapped units with the number of reported formal units, there is clear a positive tendency, with a proportional increase of both parameters from 1950 to 1993 (Figure 9). This indicates that the versions of the Geological Map of the Republic of Ecuador: Sauer (1950); S.N.G.M. and IFP, (1969); D.G.G.M. and NERC, (1982); CODIGEM and BGS, (1993), prioritize the definition of formal units. On the time space from 1994 to 2001, it is observed a similar linear behavior among these parameters, it is related to the almost no definition of new units in the DINAGE, (2001) version, if compared to CODIGEM and BGS, (1993). From 2002 to 2017 both parameters had a different behavior, it is, while the number of mapped units grew with the number of formal units it maintains a flat slope (Figura 9). This necessarily implies a growing number of informal units, pointing out that INIGEMM, (2017) did not prioritized the definition of formal mappable units.

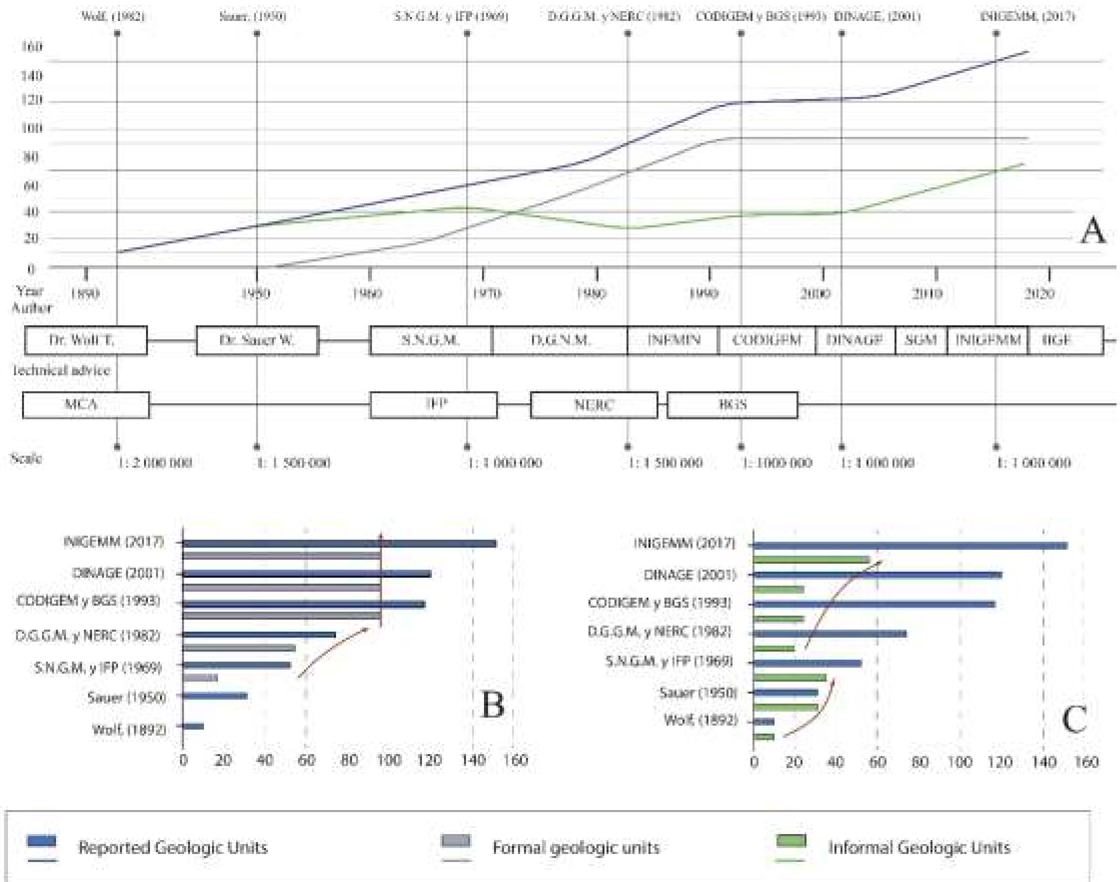

Figure 9. Statistical analysis of the reported units number on each geological research campaign. **A**. Time vs number of reported geological units on the different versions of the geological maps of the Republic of Ecuador. **B**. Bar diagram of the reported number of units vs number of informal units. **C**. Bar diagram of the reported units vs number of informal units. On the lower area of the graph A, it is represented the organization on charge for the geological mapping on a national scale, the technical advisor, and the scale of the map.

Factors influencing the proliferation of informal units on the Ecuadorian geological cartography.

Two capital characteristics for the definition of formal mappable geological units are: 1) age and 2) description of the type-outcrop, both were assessed on the different versions of the geological map.

The figure 10 depicts the relation among the number of: mappable units and the number of formal units, informal units, ages, and number of reported type outcrops. From 1950 to 1993, the parameters: reported units, formal units, and ages, maintain the same tendency with a positive slope. On the interval from 1994 to 2017, the number of reported ages on the different versions of the geological map, indicates a flat pattern. In relation to the number of type outcrops during the interval from 1950 to 1993 it is observed a positive tendency, while on the interval from 1994 to 2017 it is observed a decrease presenting a downward and flat tendency.

This analysis enables us to identify two patterns relating the definition of formal and informal units. During 1950 to 1993, the number of mapped units on the different versions of the Geological Map of the Republic of Ecuador (Sauer 1950; S.N.G.M. and IFP, 1969; D.G.G.M. and NERC, 1982; CODIGEM and BGS, 1993), was directly proportional to the number of defined formal units in function of their age and type-outcrop. While on the period from 1994 to 2017, the proliferation of informal units included on the maps (DINAGE, 2001; INIGEMM, 2017), coincides with the decline of definitions of type-outcrops and ages of the reported units.

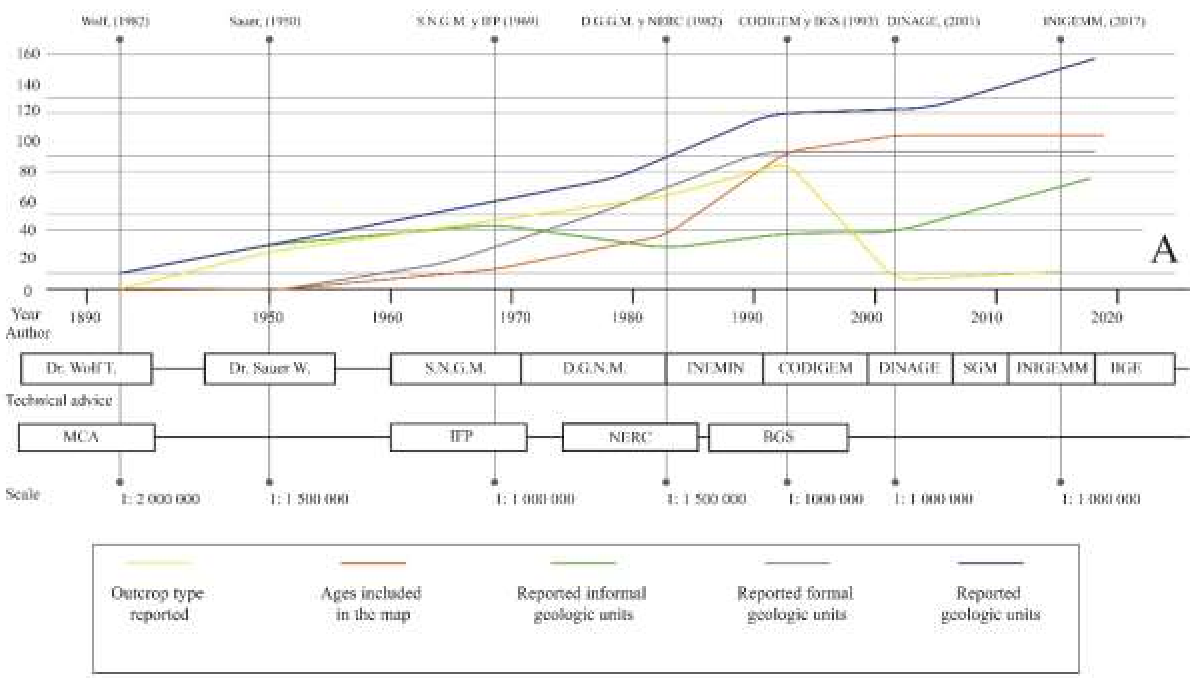

Figure 10. Statistical analysis of the number of reported regional geologic structures on each geological research campaign. On the lower part of graph A it is shown the organization on charge for the geological mapping on a national scale, the technical advisor, and the scale of the map

Number of reported geological structures.

This is another quantifiable parameter and common to the different version of the map. In this sense, Sauer (1950) included 11 regional structures, while S.N.G.M. and IFP, (1969) identified 16 faults mainly belonging to the Andes Cordillera. On the other hand, the D.G.G.M. and NERC, (1982) contain 20 structures including of the coastal region. Later, CODIGEM and BGS (1993), and DINAGE, (2001) included 32 incorporating data of the sub-Andean region. Finally, INIGEMM, (2017) contains 75 regional structures covering the whole country. Figure 11 indicates the evolution of the number of reported geological structures on every version of the Geological Map of the Republic of Ecuador along the time. This parameter presents an up-ward continuous slope, particularly on the interval between 2002 and 2017 it is observed an increase on the slope.

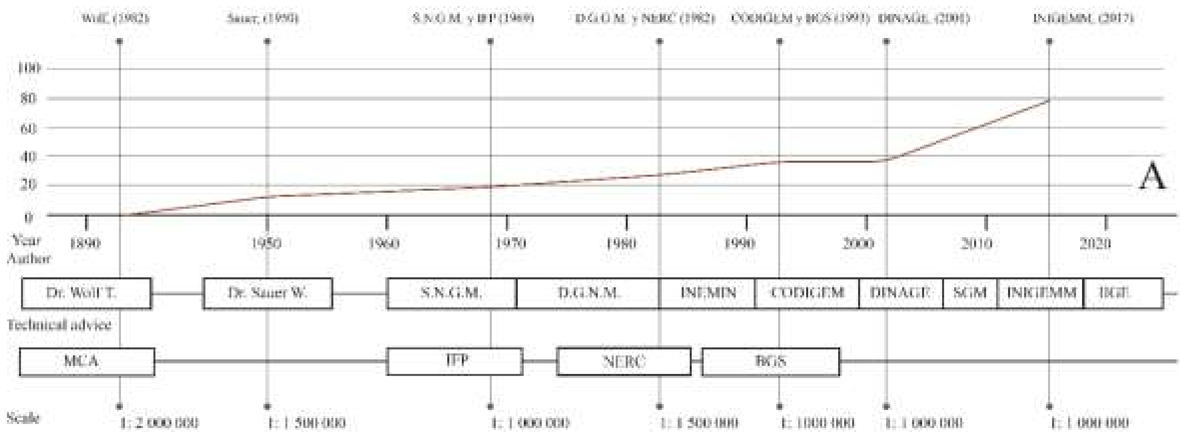

Figure 11. Statistical analysis of the number of reported regional geologic structures on each geological research campaign. On the lower part of graph A it is shown the organization on charge for the geological mapping on a national scale, the technical advisor, and the scale of the map.

Adopted measures to deal with the proliferation of informal units on the regional cartography of the Republic of Ecuador.

CODIGEM through the Proyecto de Des arrollo Minero y Control Ambiental PRODEMINCA (Mining Development and Environmental Control Project), created the Manual de Normas (Standards Manual), also dictionaries for digital SIM mapping purposes, which were the grounding for generating geological cartography for several years. Even though, informal terminology proliferated, reason for which, INIGEMM in 2016 developed a national standard for stratigraphic nomenclature, taking into account the guidelines of the International Commission on Stratigraphy (ICS), and international standards as ISO 710 for geological mapping, finally creating the document Estandarización de abreviación, simbolización y abreviaturas para el cartografiado geológico, version 1.2 (Standardization of abbreviation, symbolization and abbreviations for geological mapping, version 1.2) published with the official registration of the Ecuadorian government No. 864, on October 2016; later the IIGE updates the standards version 1.2 and creates the document: Estándares de nomenclatura estratigráfica, simbolización y abreviaturas para la cartografía geológica, version 2.0 (Stratigraphic nomenclature, symbolization and abbreviation standards for geological mapping version 2.0) published as well in the official registry No. 163 on December 2019, it is currently in use. The development of these standarization documents for stratigraphic nomenclature and its symbology on the geological cartography, were the base for the creation in 2021 of the Comisión Ecuatoriana de Estratigrafía (Ecuadorian Commission of Stratigraphy), whose objectives are the promotion and dissemination of knowledge, progress, and applications of stratigraphy nationally, specially that related to the validation of stratigraphic units in order to be formalized

CONCLUSION

Since 1892 to 2017, it has been published 7 versions of the Geological Map of the Republic of Ecuador: Wolf, (1892); Sauer (1950); S.N.G.M. and IFP, (1969); D.G.G.M. and NERC, (1982); CODIGEM and BGS, (1993); DINAGE, (2001); INIGEMM, (2017). Every version contributed to the development and understanding of the regional geological framework. Advances on regional cartography are reflected on the discrimination of mappable geological units, currently being 152 recognized (INIGEMM, 2017). However, in the last two decades, it was observed a proliferation of informal geological units (DINAGE, 2001; INIGEMM, 2017). This is related to the lack of standardized criteria for defnition and characterization of outcroops formations, and the absence of ages for the mapped units.

Every version of the map was the result of the scientific contribution of international missions, private sector specially mining and oil, and academic research conducted by different government research institutes, with technical advice of foreign research institutes. Throughout Ecuador's history of geological research, the most efficient public policies in geological mapping involved cooperation with foreign geological research institutes.

In the future, geological cartography in Ecuador must contribute to the formal definition of outcrops and type sections and should include relative and absolute ages of rock sequences to formalize informal units.

The socialization of the "Estándares de nomenclatura estratigráfica, simbolización y abreviaturas para la cartografía geológica" (Stratigraphic nomenclature, symbolization, and abbreviations standards for geological mapping) to in the academic community and industry of the country is necessary, with the objective of unifying criteria in geological cartography and working on the construction of the eighth version of the geological map of the Republic of Ecuador

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