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Overview of the geological mapping in Brazil: historical analysis until 2022

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Abstract

The purpose of this work is to contextualize the evolution of the geological mapping in Brazil since the creation of Company of Research of Mineral Resources (*CPRM-Companhia de Pesquisa de Recursos Minerais*), in 1969, as part of a set of governmental measures that aimed to boost the Brazilian mineral sector. Three mapping cycles were individualized (1969-1993, 1994-2002, and 2003-2022) over such 53 years, which time limits were defined by historic milestones, and which differ between them especially due to the methodological approach and to the support tools available. The analysis was carried out strictly considering 1:250,000 and 1:100,000 scales, which represent the main reference scales of geological cartography in Brazil. The assessing of the performance of the mapping shows that the level of the geological knowledge of the country is still incompatible with its mineral potentialities, with its strength in other natural resources, and with its importance in the world scenario. Only 48% of the Brazilian territory are mapped at the 1:250,000 scale, and 27% in 1:100,000 scale. Amazon represents the territory with lower geological knowledge, since less than 40% of such territory have mapping coverage in 1:250,000 scale. In contrast, more than 50% of the non-Amazon areas are mapped at the 1:100,000 scale. Over the period under analysis, emphasis was given to the Precambrian shields in relation to the sedimentary basins, which configure large cartographic gaps, as well as critical Precambrian areas of the Amazon, for example, a large part of the Guiana Shield, in the northern margin of Amazon River. In addition to the challenge of mapping a country of continental dimensions and with heterogeneous geoeconomic contexts, other factors contribute to this scenario, among them, the discontinuity of governmental initiatives and programs, which directly affect the planning of the mapping, the budget for investments in projects, human resources, infrastructure, and on the articulation of productive partnerships. This review shows that the periods of greater productivity in the geological mapping were a consequence of well-defined governmental guidelines, proper investments, and sharing of responsibilities with State governments and Brazilian universities, for example, such as happened in countries that had the perception of the importance of basic geological surveys as a strategy for development.

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1. Introduction

The geological mapping involves a specialized multidisciplinary approach of the Geosciences, and represents the base of knowledge of the physical space, on which other spheres of knowledge, research and geoscientific application are set forth. The geological mapping, associated with geophysical and geochemical surveys, and the integrated analysis of the data and information generated, unmistakably reduces the exploratory risk, stimulates investments in mineral research, and leads to the discovery of new mineral deposits. In addition, geological mapping is essential as support for other derivative activities, such as the research and the management of superficial and underground water resources, the understanding of landscape evolution, including the origin of soils, the geodiversity studies, the identification of areas of geological hazards, and the actions aimed at management, planning, and occupancy of the physical space. The role of basic geological knowledge as a support and driver of the academic activities of teaching and research in Geosciences is also highlighted.

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The understanding of the importance of geological mapping dates back to the 19th Century, when it induced the creation of the first geological services around the world, under the premise that it was the State's assignment to promote geological knowledge, fundamental for the development of the industry, mining, agriculture, and planning of the regional development. This perception led to the consolidation of the Geology at a global scale.

Worldwide, it is the responsibility of governmental institutions to carry out and/or coordinate the geological mapping in countries, with national and state/provincial geological services being the major players in such a task. This is also the case in Brazil, where the Geological Survey of Brazil represents the institution of the Federal Government, responsible for conducting systematic geological mapping programs, although there are significant contributions of State institutions of geology and mining, and of Brazilian universities.

This work presents an overview of the geological mapping in Brazil from the creation of the Company of Research of Mineral Resources *(CPRM-Companhia de Pesquisa de Recursos Minerais)*, in 1969, a public company linked to the Ministry of Mines and Energy, which emerged among its main assignments, to carry out the coverage of geological mapping of the country, a commitment that has enhanced and consolidated after its transformation into Geological Survey of Brazil, in 1994.

Adopting 1:250,000 and 1:100,000 scales of geological cartography as a reference, this work discusses the evolution of the mapping along three cycles that occurred between 1969 and 2022, including the advances achieved and limitations, the influence of public policies on the performance of the execution, as well as a brief analysis of the geological mapping in other countries is presented. It is highlighted that it was considered in this analysis the mapping carried out by public and private institutions, and which geological maps are of public domain.

With this approach, it is expected to contribute to the planning and definition of actions that improve the geological knowledge of Brazil, a paramount condition to promote the progress of the geoscientific knowledge and to the economic and social development of the country.

2. Historical highlights in the trajectory of the geological mapping in Brazil

The creation of several geological services in the 19th Century in the world (e.g., Great Britain 1832, Canada 1842, France 1868, USA 1879, Russia 1882, among others), according to Figuerôa (1997), marks the institutional development of the geological sciences, especially due to the establishment of the geological mapping as a special way to carry out scientific research and present results, leading to the consolidation of the Geology worldwide.

After some initiatives aimed at boosting the geological research in the country, and following the model of other countries, in the early 20th Century, it was created the Geological and Mineralogical Service of Brazil *(Serviço Geológico e Mineralógico do Brasil*), in 1907, considered the first governmental institution dedicated to the national geological surveys, with emphasis on the regional geology and mineral resources, and on the study of the superficial and underground waters.

After a short period of operation, the *Serviço Geológico e Mineralógico do Brasil* was incorporated into the National Department of Mineral Production *(DNPM-Departamento Nacional de Produção Mineral*), created in 1934, as a result of reforms promoted during the "Vargas Era" (referring to the President Getulio Vargas). The foundation of DNPM is understood as one of the actions resulting from the Federal Constitution of 1934, which improved the regulatory framework for mining in the country and disconnected the properties of soil and subsoil, then becoming a liability of the Federal Government to legislate on the underground wealth. Upon such context, it was urgent to have a governmental body to promote the development of the mineral sector, and the DNPM arose having among its main assignments to carry out the geological mapping of the Brazilian territory, until the creation of *Companhia de Pesquisa de Recursos Minerais-CPRM* (Decree-Law 764, 07/15/1969), in 1969.

In addition to the creation of CPRM, several milestones occurred throughout the 1960s show a phase of consolidation of Geology in Brazil, as pointed out by Bertoldo (2000), highlighting the creation of the Ministry of Mines and Energy, the launch of the *I Plano Mestre Decenal para Avaliação de Recursos Minerais do Brasil 1965-1974* (Decennial Master Plan for Assessment of Mineral Resources of Brazil), the enactment of the Mining Code of 1967, the promotion of the DNPM, the creation of the first State-owned companies of geology and mining (e.g., METAGO-Goiás), the graduation of the first geologists in the courses created in 1957, the implementation of an intense campaign to study sedimentary basins by PETROBRAS, and the discovery of iron in Carajás (Pará State), which decisively boosted the mineral research in Amazon.

From the start of the operations, in 1970, CPRM gradually undertook the role of State institution responsible for the geological mapping of Brazil, replacing the assignment until then conducted by DNPM.

Large investments in geology and mining were made by the Federal Government in the 1970s and, additionally to CPRM, NUCLEBRÁS and DOCEGEO (by *Companhia Vale do Rio Doce*) began their activities, and it was started the pioneering studies of the Brazilian continental shelf through the Recognition of the Continental Margin Project (Projeto REMAC – Reconhecimento da Margem Continental). At the State scale, the *Companhia Baiana de Pesquisa Mineral- CBPM*, the *Minerais do Paraná-MINEROPAR*, and the *Departamento de Recursos Minerais do Estado do Rio de Janeiro-DMR* were created, which carried out geological mapping programs, contributing significantly to the achievement of the current coverage of geological mapping of the national territory.

When discussing geological mapping in Brazil, it is essential to mention some initiatives that marked the history of systematic mapping, whether at the local or regional level. It stands out the program of geological cartography in detail scale (1:25,000 scale) carried out in the Iron Quadrangle (*Quadrilátero Ferrífero*), based on the cooperation signed between the DNPM and the United States Geological Survey (USGS), in 1945. This program, executed by American and Brazilian geologists and engineers, culminated with the publication of the geological map of the Iron Quadrangle in 1969 (Castro et al. 2000), starting a virtuous history of geological mapping in the state of Minas Gerais. In Paraná, the Committee of Geological Chart of Paraná was created in

1994, which resulted in the production of geological maps at the 1:50,000 and 1:70,000 scales (IAT 2022).

During the effervescence of the 1970's, the RADAM-*Radar da Amazônia* Project was launched, which was extended to the entire national territory under the designation of RADAMBRASIL Project. This notable project operated until 1985, coordinated by the Ministry of Mines and Energy, through the DNPM, financed with resources of the *Plano de Integração Nacional-PIN* (National Integration Plan), and represented a pioneering effort of the Brazilian government in the research of natural resources, which, through the publication of geological maps of cartographic sheets in 1:1,000,000 scale, unquestionably structured the base of the regional geological knowledge of the Brazilian territory.

In early 1980s, the *II Plano Mestre Decenal* 1981-1990 (Decennial Mining Master Plan) was launched, which guided the carrying out of regional geological mapping, mainly in the Amazon, and semi-detail geological surveys in more promising targets for the discovery of new deposits.

In 1994, CPRM was transformed into a public company (Law no. 8,970, 12/28/1994), becoming the Geological Survey of Brazil and expanding its scope of action, especially by the incorporation of new lines of work related to the Geodiversity, to the research in the marine territory and support for public policies of planning and management of the physical space. Even so, geological mapping remains as one of its paramount activities, being the most relevant governmental institution in the performance of the coverage of geological mapping in Brazil, and in the systematization, organization, and dissemination of geoscientific knowledge.

3. Cycles of systematic geological mapping

In this analysis of the evolution of geological mapping in Brazil, from the creation of the CPRM until 2022, the main reference scales of 1:250,000 and 1:100,000 were considered, based on the understanding that the first is fundamental in areas of lower geological knowledge, especially in the innermost portions of the Amazon, and that the second is the minimum scale to assess the mineral potential of the worked areas. It is also included in the analyses of the mapping programs made by other institutions, for example, the State geology and mining companies (e.g., CBPM-Bahia, COMIG-CODEMIG-Minas Gerais, MINEROPAR-Paraná), service providers (e.g., PROSPEC S.A.) and Brazilian universities.

It should be noted that, although only two reference scales are addressed in this work, several initiatives of geological mapping are recognized, carried out at scales with greater detail, conducted by Brazilian universities and other institutions (e.g., SUDENE, CNEN, IPT, DNPM), which provided important contributions in specific areas and geological objects, which positively impacted later mapping programs, carried out at the 1:250,000 and 1:100,000 scales.

Three cycles or phases of geological mapping were characterized, and defined from historical landmarks, which diverge between themselves especially due to the methodological approach and the support tools available in each cycle. Although strict time limits have been established, such cycles developed in a transitional manner, so that the characteristics or actions of a cycle in some cases may extend into the early stages of the subsequent cycle. Figures 1 to 3 show the cartographic sheets mapped in each cycle at 1:250,000 and 1:100,000 scales.

3.1 Cycle 1969-1993

The 1969-1993 cycle starts with the creation of CPRM, and extends during its phase as a mixed-capital company, which actuated in the prospection of mineral deposits, through projects carried out from requests issued by DNPM. It includes pioneering mapping projects, especially aimed at regional geological recognition, especially in the Amazon, due to the operational and logistic difficulties in the sectors with more preserved biome, while in non-Amazonian areas (Northeast and Center-South geoeconomic regions) there has already been a greater evolution of systematic geological cartography.

In this cycle, it is highlighted the performance of the *Programa de Levantamentos Geológicos Básicos-PLGB* (Basic Geological Surveys Program), from 1985 onwards, boosted by the launch of the II Decennial Mining Master Plan (1981-1990). The PLGB may be considered the first national program of systematic mapping on a semi-detail scale promoted by the Federal Government, which resulted in important advances in geological knowledge, but at a variable level in the different geoeconomic regions of the country.

Over this 24-year cycle, there were oscillations in terms of investments in geological cartography, the evolution of the available technological resources, and approach of the projects carried out, but these may be considered as general characteristics of the projects carried out: 1) Use of conventional aerial photographs and radar images; 2) Partial or full support of field data in the worked areas, in case of projects of regional recognition or systematic cartography, respectively; 3) Partial support of laboratory analyses; 4) Use of analogical cartographic bases (SGE, IBGE, etc.); 5) Non-routine use of airborne geophysics as subside to the geological cartography.

3.2 Cycle 1994-2002

The starting point of the 1994-2002 cycle is the transformation of the CRPM into the Geological Survey of Brazil, when the mission of carrying out geological mapping in the country was reinforced. The Geological Survey of Brazil arose with the governmental attribution of planning, performing, and coordinating the second phase of the *Programa de Levantamentos Geológicos Básicos-PLGB* (Basic Geological Surveys Program) (Decree 917/93, of 09/08/1993), to be carried out until 1999. This second phase of the PLGB, fully coordinated by the Geological Survey of Brazil, prioritized the 1:250,000 and 1:100,000 scales for systematic mapping in Amazonian and non-Amazonian areas, respectively, and advocated the geological-geochemical-geophysical multidisciplinary integration to support the metallogenic assessment and the mineral potential of worked areas. Among the goals set forth by PLGB was the carrying out of 1:250,000 mapping in the Precambrian shields of Amazon, in a total area of 1,270,000 km², and at the 1:100,000 scale in selected areas of the other regions, amounting to 252,000 km².

This cycle, lasting just eight years, is understood as transitional between the previous historical phase and the time of transformations that occurred in the first years of the

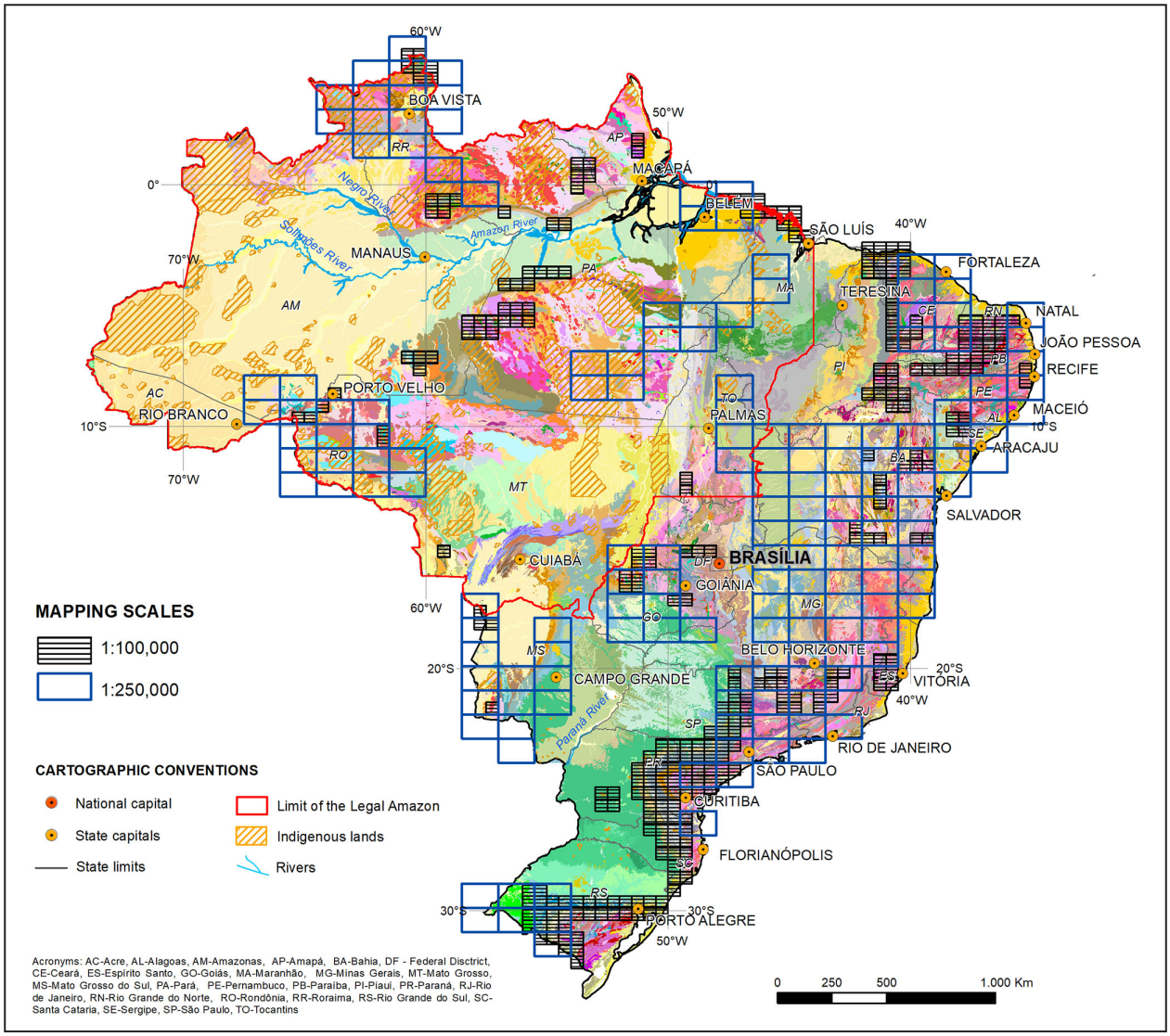

FIGURE 1. - Distribution of the mapped areas in Brazil in cycle 1969-1993.

second millennium, especially marked by the incorporation of new geotechnologies as support to the geological mapping. Some resources in this cycle sum to those of the previous phase, highlighting: 1) Using of satellite images; 2) Full support of field data, considering that the purpose of the projects was systematic cartography; 3) More advanced laboratory resources and techniques (e.g., whole-rock geochemistry, geochronology, and multi-elementary geochemistry); 4) Greater application of airborne geophysics in the geological cartography; 5) Start of the incorporation of new geotechnologies, such as the use of digital cartographic bases, positioning through GPS (Global Positioning System) in some projects and insertion of the concept of computational databases.

3.3 Cycle 2003-2022

The 2003-2022 cycle marks the maturity of the Geological Survey of Brazil. It represents the most productive cycle of systematic mapping, and it is especially characterized by the implementation of geotechnologies in the geological cartography, which became to play an important role in the development stages of the projects and in the quality of the products. The geological mapping passed to be carried out on georeferenced bases, in a Geographic Information System (GIS) environment, with support of remote sensing images, laboratory techniques with higher analytical accuracy and, in general, being programmed in areas with availability of airborne geophysical coverage. The following stand out as support to the geological mapping: 1) Use of digital and georeferenced cartographic bases; 2) Use of GPS in all projects; 3) Diversity of remote sensing images with multiple applications; 4) More robust laboratory analytical methods (e.g., geochronology/isotopic geology, Scanning Electron Microscope-SEM, electron microprobe, etc.); 5) Systematic application of high resolution (compatible with the scale up to 1:100,000) airborne geophysics (magnetometry and gamma-spectrometry) in the geological cartography; 6) Full implementation of GIS technology; 4) Creation of GEOBANK/GEOSBG, the corporate database that integrates geoscientific databases (e.g., outcrops, mineral resources, geochronology, geochemistry, etc.), enabling a wide availability of data generated by the mapping.

The publication of the geological map at 1:2,500,000 scale and the set of 45 cartographic sheets at 1:1,000,000 scale

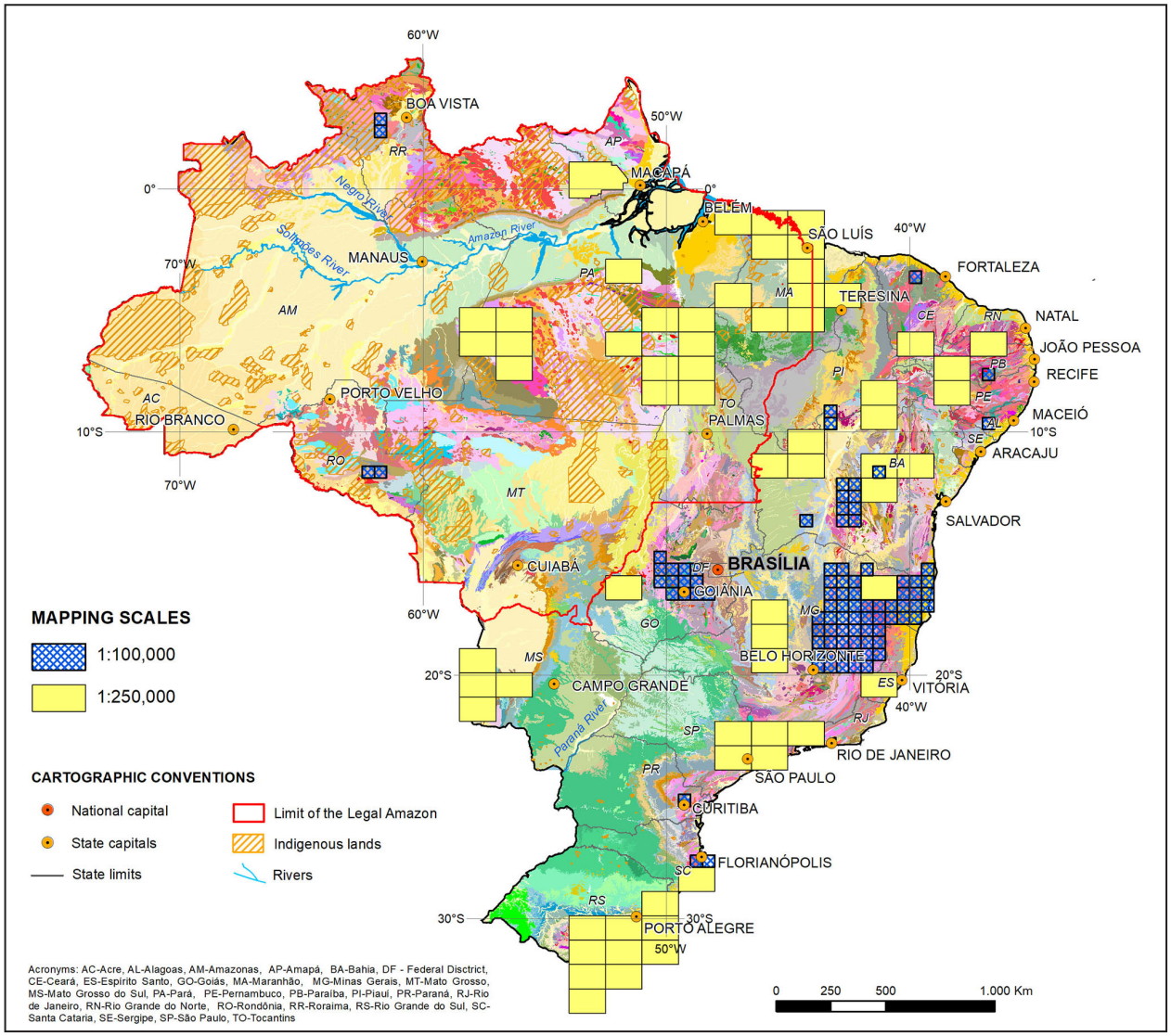

FIGURE 2. - Distribution of the mapped areas in Brazil in cycle 1994-2002.

that covered the whole national territory, in 2003 and 2004, respectively, fully prepared in GIS environment, is considered a milestone, from which the application of geotechnologies in the systematic geological cartography became routine in the Geological Survey of Brazil.

Regarding the governmental programs, after a phase of higher investments in PLGB (Basic Geological Surveys Program) occurred in the previous cycle, there was an acquiescence period of the geological mapping in the Geological Survey of Brazil, especially due to budgetary restrictions influenced by oscillations in the country's economy. The resumption of the systematic geological surveys took place through the Geology of Brazil Program (Programa Geologia do Brasil-PGB), bound to the Multiannual Plan 2004-2007 of the Federal Government.

It is important to highlight, in this context, the relevance of the Multiannual Plans as a constitutional instrument (Art. 165) of governmental planning, since they define the guidelines, purposes, and goals of the public administration for 4-year cycles. Through the Geology of Brazil Program, the Geological Survey of Brazil was enrolled in the Multiannual Plan of the Federal Government. The Geology of Brazil Program advocated the acceleration of the geological knowledge in the country, providing technical subsidies to attract new investments in mineral research, and to resume a new mining cycle. Among the guidelines set forth, the Geology of Brazil Program also defended the preferential adoption of 1:250,000 scale in Amazon, and 1:100,000 scale in the rest of Brazil.

From the Geology of Brazil Program, the Geological Survey of Brazil was considered in other programs that allowed access to additional budgetary resources that financed several activities in the company, including the geological mapping, in addition to the geochemical and airborne geophysical surveys, fundamental for the exploration mineral potential assessment. In 2008, the Geological Survey of Brazil became part of the *Programa Cartografia da Amazônia* (Cartography of the Amazon Program), coordinated by the *CENSIPAM-Centro Gestor e Operacional do Sistema de Proteção da Amazônia* (Managing and Operational Center of the Amazon Protection System), which forecast the performance of the Land Cartography, Nautical Cartography, and Geological Cartography subprojects, the latter under the responsibility of the Geological Survey of Brazil. In 2009, the Geological Survey of Brazil entered the PAC-Programa de Aceleração

do Crescimento (Growth Acceleration Program), on the understanding that geological knowledge was essential for planning infrastructure works in Brazil.

Upon the need for faster advancing in the geological knowledge of the country, PRONAGEO was created in 2005, through which the Geological Survey of Brazil entered into a contract with around 20 Brazilian universities, aiming at the mapping of cartographic sheets, especially in the 1:100,000 scale, in projects coordinated by nationally renowned professors-researches, in general, leaders of research groups at their original universities.

Since 2004, the basic surveys coordinated by the Geological Survey of Brazil are continuously bound to the Multiannual Plans of the Federal Government. The Geology of Brazil Program was extended to the Multiannual Plan 2008-2011, followed by the Strategic Management of Geology, Mining, and Mineral Transformation (Multiannual Plan 2012-2015) and Geology, Mining, and Mineral Processing programs (Multiannual Plans 2016-2019 and 2020-2023).

During a phase of significant investments in basic surveys (geological, geochemical, and geophysical) carried out by the Federal Government, it was launched, in 2011, the National Mining Plan 2030 (PNM-*Plano Nacional de Mineração* 2030 (MME 2011), which contained the goals for the geological mapping to the subsequent twenty years: 1) To map 100% of the Amazon in 1:250,000 scale, and 2) To map 100% of the non-Amazonian areas in 1:100,000 scale. Thus, it should be mapped around 2.5 million km² in Amazon, and 2.1 million km² in non-Amazon areas. If such goals were complied with, 91% and 47% of the Brazilian territory would be mapped in 1:250,000 and 1:100,000 scales until 2030, respectively. Such goals had as starting point the premise that, in 2010, 50% of Amazon was already mapped in 1:250,000 scale, and that 40% of the non-Amazon territory already had coverage of mapping in 1:100,000 scale.

Other guidelines were postulated in PNM 2030 for the definition of priority of areas to be mapped, which in summary should represent: 1) Cartographic gaps; 2) Areas of relevant mineral interest; 3) Indigenous lands in 5% of the area to be mapped in Amazon in 1:250,000 scale); 4) Sedimentary basins in 15% of the area to be mapped in 1:100,000 scale in non-Amazon areas. The bold goals of PNM 2030 were designed at a time of economic growth of Brazil, and higher investments in basic geological surveys, which unfortunately decreased over time.

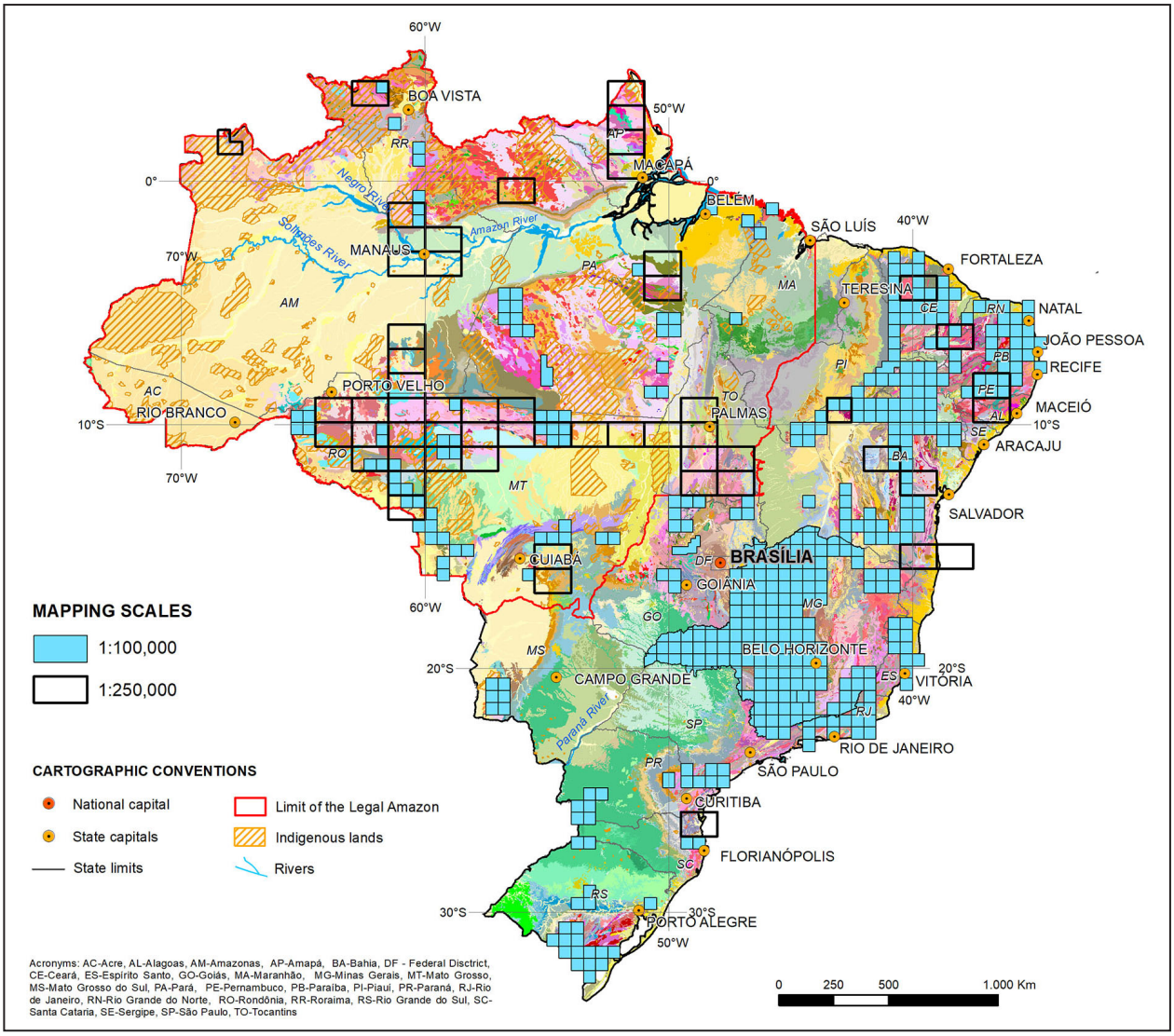

FIGURE 3. - Distribution of the mapped areas in Brazil in cycle 2003-2022.

4. Current stage of geological mapping

The percent calculation of mapping coverage carried out between 1969 and 2022, therefore incorporating the three cycles of performance, shows that: 1) 48% of the Brazilian territory is mapped at the 1:250,000 scale, and 27% at the 1:100,000 scale; 2) 63% of the non-Amazonian area are mapped at the 1:250,000 scale, while 37% of Amazon are mapped in such scale; 3) 55% of the non-Amazonian area are mapped in 1:100,000 scale, while 8% of Amazon are mapped in such scale (Figure 4, Table 1).

For calculation, it was adopted the accurate areas of 18,000 km² and 3,000 km² for the 1:250,000 and 1:100,000 cartographic sheets, respectively. Overlaps that occurred in case the same sheet was mapped in more than one mapping cycle were excluded, as well as areas of cartographic sheets that cover oceanic and international zones were disregarded.

The analysis of the mapped areas (Figures 5, 6) shows the priority of the Precambrian shields areas in the mapping programs, to the detriment of the sedimentary basins, as well as the non-Amazonian area was a priority, in detriment of Amazon. Almost the total of the shield areas of the non-Amazonian territory is mapped at the 1:250,000 scale since the first cycle of mapping, which enabled the evolution of the cartography at the 1:100,000 scale, or more detailed scale, in the following cycles, especially in the areas of higher mineral potential, such as the Quadrilátero Ferrífero (Iron Quadrangle, state of Minas Gerais), Seridó-Cachoeirinha (states of Rio Grande do Norte, Paraíba, and Pernambuco), Jacobina Mountain (state of Bahia), Tróia-Pedra Branca (state of Ceará), Palmeirópolis/Niquelândia (states of Goiás and Tocantins), among others.

On the other hand, in more than 60% of Amazon, the geological knowledge still remains at a level of regional recognition, even in areas of Precambrian shields, such as, for example, the region of Xingu River basin (state of Pará), and a large part of the Guiana Shield, in North of Amazon River channel, which still do not have mapping coverage in 1:250,000 scale.

Some factors contribute to the deficit of knowledge in Amazon, including the higher costs to carry out the field

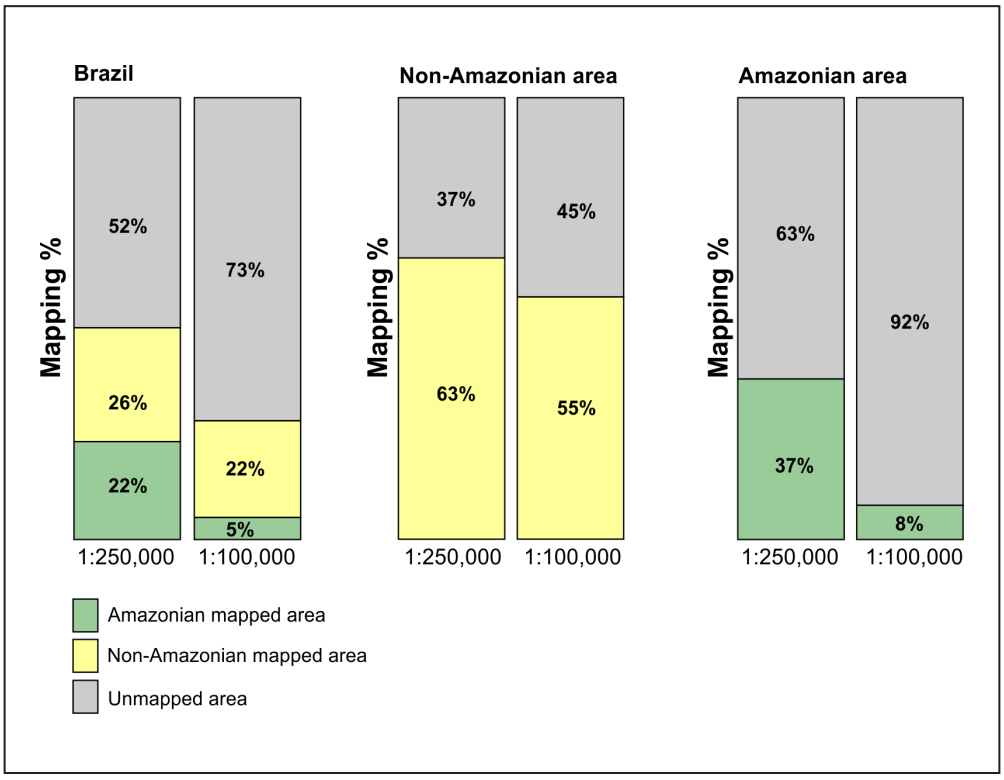

FIGURE 4. - Illustrative histograms of the percentages of mapping in 1:250,000 and 1:100,000 scales in Brazil and in Amazon and non-Amazonian territory.

TABLE 1. Percentages of mapping carried out in 1:250,000 and 1:100,000 scales.

Scale	Territory	Mapped area (km²)	% Brazil	% of the territory
1:250,000	Brazil	4,043,157	48	-
	Amazon	1,854,843	22	37
	Non-Amazonian	2,188,313	26	63
1:100,000	Brazil	2,294,689	27	-
	Amazon	384,141	5	8
	Non-Amazonian	1,910,548	22	55

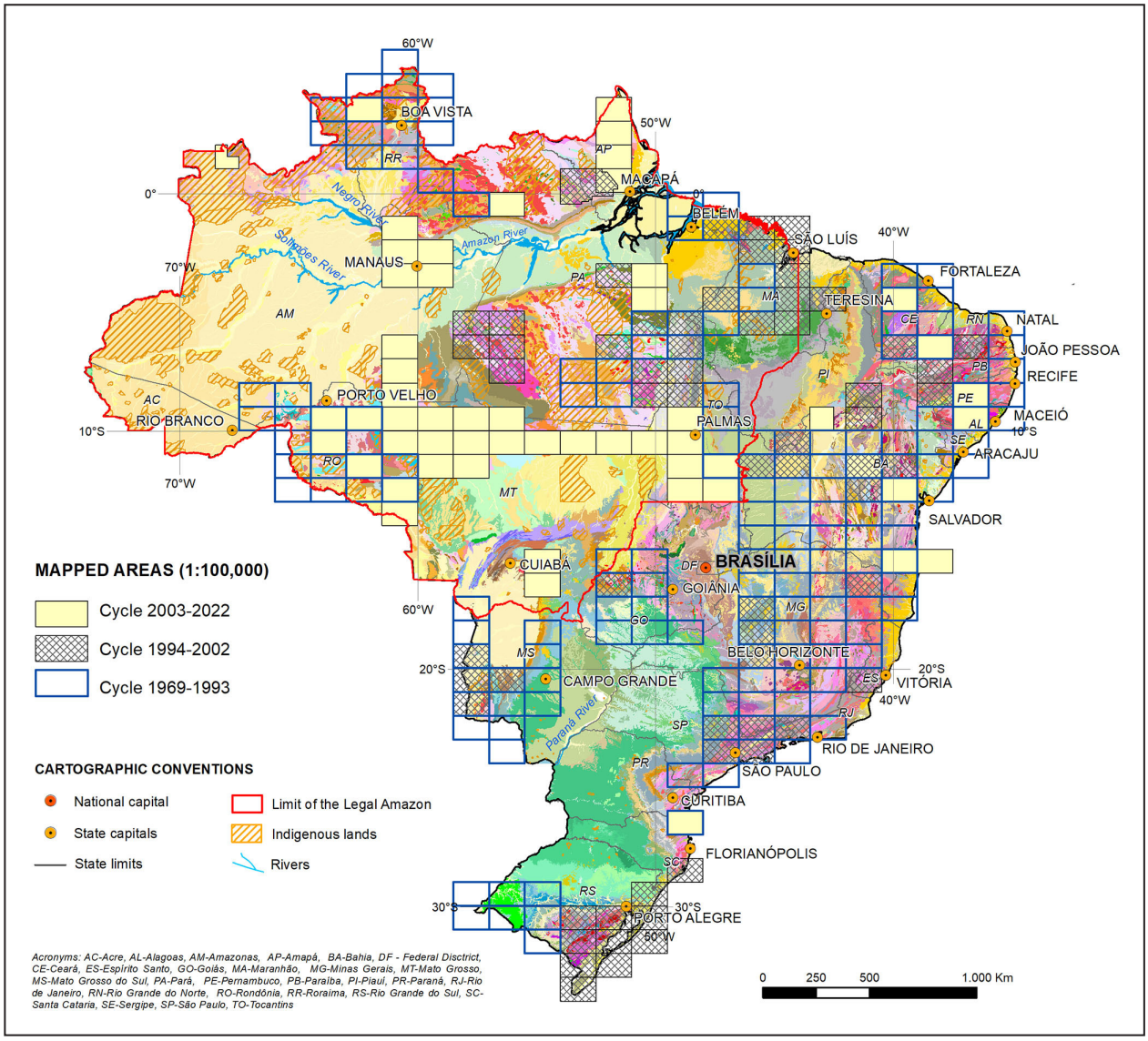

FIGURE 5. - Distribution of the mapped areas in Brazil at the 1:250,000 scale between 1969 and 2022.

surveys, especially in areas of preserved biome, and also for having extensive areas of sedimentary basins (Amazonas-Solimões, Parnaíba, and Parecis), geological objects historically left in second plan in the geological cartography programs, since the study of the basins was in charge of PETROBRAS, which despite having made huge progress in the research of fossil fuels of Brazilian basins, has not always performed systematic cartography.

If surveys from the 1969-1993 cycle are disregarded, which were not always performed systematically and compatible with the scale of presentation of the geological maps, and with higher limitation of the support tools, the scenario becomes increasingly deficient, and the challenges increase.

The best-known areas of Amazon represent mineral provinces with consolidated exploratory activity, or under consolidation, formal or not, such as, for example, Carajás and Tapajós in the state of Pará, Pitinga (Amazonas), and Juruena-Teles Pires Alta Floresta (state of Mato Grosso), but even though the knowledge is still inconsistent with their strategic importance and mineral potential.

A good example is the region of Carajás, the most important mineral province of the country and one of the largest in the world, which still does not have complete geological cartography at the 1:100,000 scale, which strongly contrasts with the Iron Quadrangle, even if the due proportions are considered, where systematic geological surveys were started in the 1940s, by the previously mentioned mapping program of DNPM-USGS agreement, now counting with updated cartography at the 1:25,000 scale.

The state of Minas Gerais as a whole presents a significantly more advanced level of geological cartography in relation to other states, since almost the entire State, with more than 586,000 km², has systematic geological cartography at the 1:100,000 scale. It is a didactic example that shows that the sum of efforts and the sharing of responsibilities results in greater efficiency, since the current mapping coverage in Minas Gerais represents the sum of projects carried by the Geological Survey of Brazil, by the State government, through *Companhia Mineradora de Minas Gerais* (COMIG) and *Companhia* de *Desenvolvimento Econômico de Minas Gerais* (CODEMIG), and by Brazilian universities, notably the Federal University of Minas Gerais (*Universidade Federal de Minas Gerais,* UFMG), financed by initiatives such as PRONAGEO and by the State government itself (Figure 7).

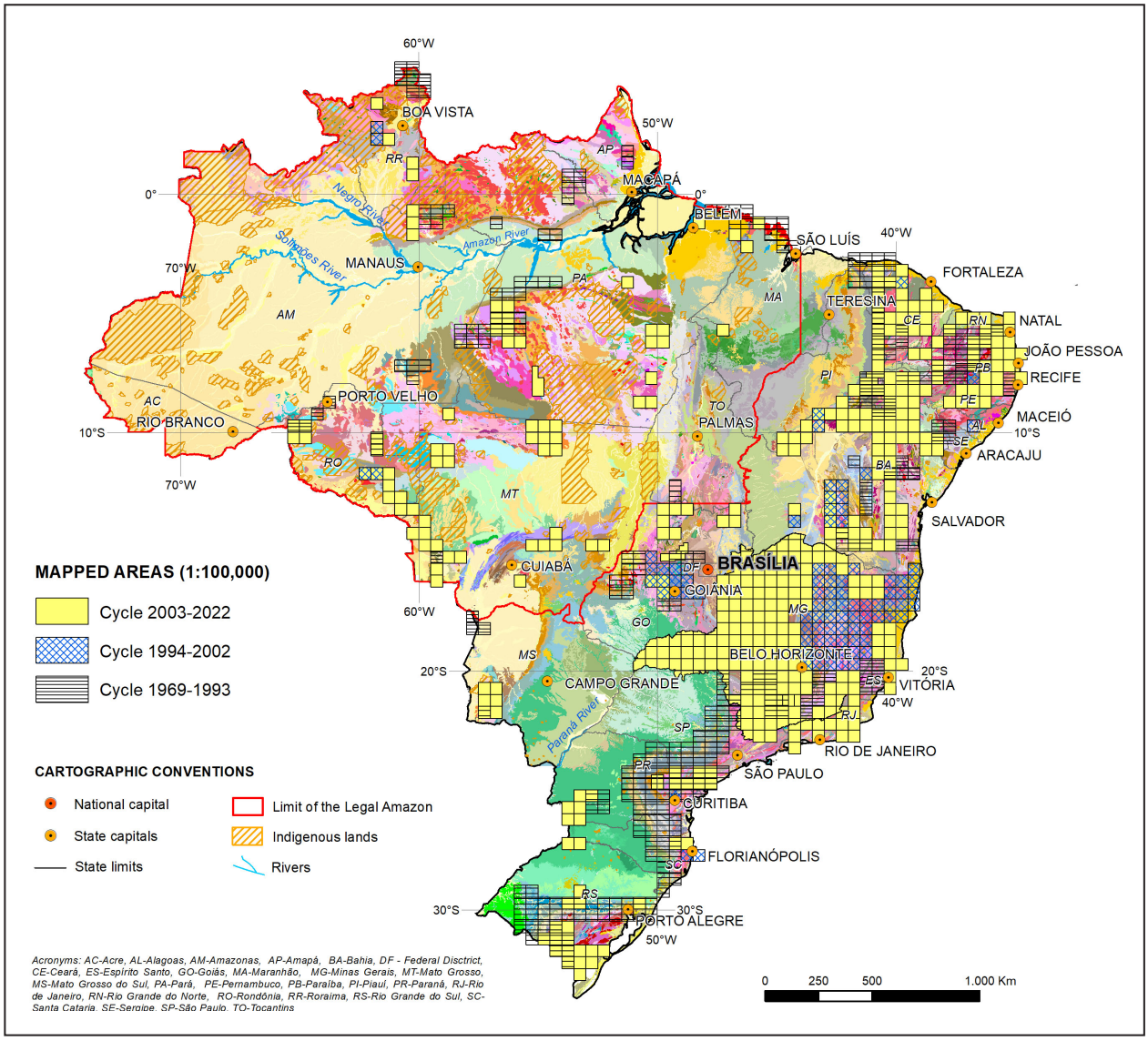

FIGURE 6. - Distribution of the mapped areas in Brazil at the 1:100,000 scale between 1969 and 2022.

Although great efforts have been made by the Geological Survey of Brazil throughout its history, in addition to the important contribution of State governments and Brazilian universities, extensive areas of the national territory remain with insufficient or outdated geological knowledge, or with cartographic gaps. In general, what can be seen is that the level of geological knowledge in Brazil still is inconsistent with its mineral potential, its strength in other natural resources, and the importance of the country in the world scenario.

5. Reflex of governmental initiatives in the performance of the geological mapping in Brazil

Throughout the development of the three cycles, whenever there were governmental initiatives and budget availability to perform mapping programs, there was greater productivity and agility in mapping. Figure 8 presents a histogram showing the number of geological maps (1:250,000 and 1:100,000 scales) published between 1970 and 2022, as well as the programs and initiatives over the period are highlighted. In the interpretation of Figure 8, it shall be considered that in a mapping project, the publication of the geological map occurs in the years after the project's highest investments phase, which basically represents the costs with field surveys and laboratory analyses.

In a first analysis, high productivity can be observed in cycle 1969-1993, especially in the mid-1970s, being certainly a reflection of investments and transformations that occurred from the second half of the 1960s, such as the launch of the I Decennial Master Plan for Assessment of Mineral Resources of Brazil and the creation of CPRM.

In the first cycle, the 1:250,000 scale was a priority, which is compatible with that time when the geological knowledge was still very elementary at a regional scale, even in non-Amazonian area. An isolated highlight in the year 1986 refers to the publication of 99 maps (1:100,000 scale) by the *Borda Leste da Bacia do Paraná Project*, which aimed to collect, align, and integrate data generated since the 1960s by several companies (PETROBRAS, CPRM, PAULIPETRO, NUCLEBRÁS, MINEROPAR), focused on the research of coal on the western edge of the basin.

Although there are important production highlights in the cycle 1994-2003, such as in 1997 and 2000, and which especially refer to the results of the Basic Geological Surveys Program (PLGB-

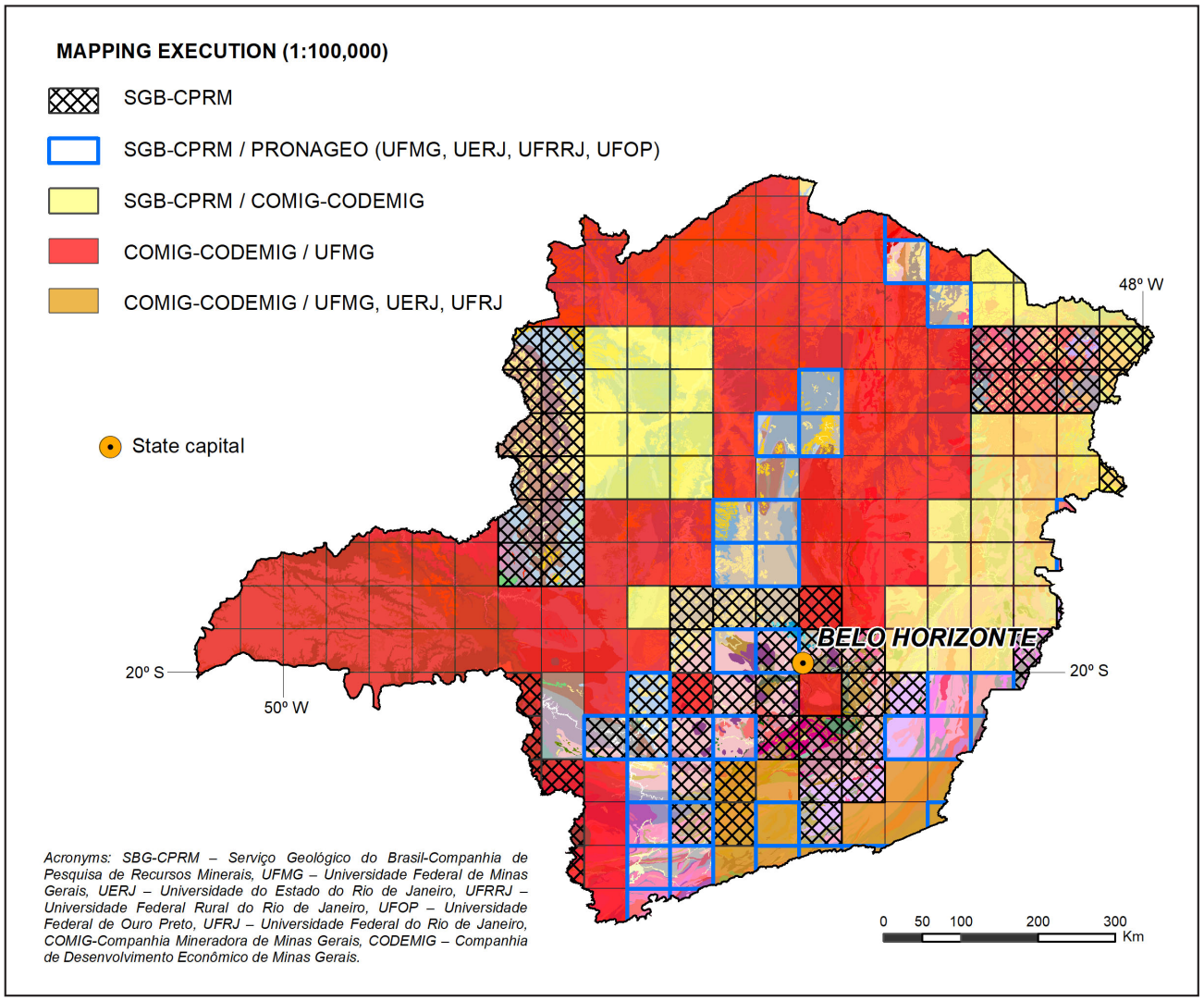

FIGURE 7. - Coverage of the geological cartography at the 1:100,000 scale in the state of Minas Gerais.

Programa de Levantamentos Geológicos Básicos), the same vigor of the 1970s was not achieved in this cycle.

The 1980s and 1990s, which represent the transition between two cycles of geological mapping, were critical periods in the economy of the country. The CPRM was threatened with extinction and some State institutions of geology and mining actually extinguished, with repercussions on the production of basic geological knowledge, since the financial resources at the Federal and State government levels were very limited.

Undeniably, the cycle 2003-2022, where the 1:100,000 scale was a priority, represents the phase of greater productivity of geological maps, especially in the period 2011-2015, mainly reflecting the investments made since the conception of the Geology of Brazil Program (PGB-*Programa Geologia do Brasil*), bound to the Multiannual Plans of the 2004-2007 and 2008-2011, which passed to count on financial resources of the Annual Budget Law (LOA-*Lei Orçamentária Anual*), and those from the Cartography of the Amazon Program and of the Growth Acceleration Program (PAC-*Programa de Aceleração do Crescimento*), from 2008 and 2009, respectively. The performance of PRONAGEO favors such a phase of greater productivity which, with the application of resources of the Geology of Brazil Program, led to the mapping of more than 100 cartographic sheets at the 1:100,000 scale by Brazilian universities. Additionally, investments made by State governments financed systematic mapping programs, with emphasis on COMIG-CODEMIG, in Minas Gerais.

When the National Mining Plan 2030 (PNM 2030) was launched in 2011, the moment was one of optimism in relation to the Brazilian economy, with the expectation of average growth of around 5.1% per year, even surpassing the forecast of growth of the world economy, from 3.8% per year (MME 2011). To promote such improvement of geological knowledge considering the strategic purpose of the PNM 2030, investments of over R$ 1 billion were estimated between 2011 and 2030, with a forecast of an annual budget over R$ 55 million, which would include, in addition to the geological mapping, the geophysical and geochemical surveys, and the study of mineral resources.

However, from the analysis of the budget made available to the Geological Survey of Brazil, what is observed is a pattern of strong budget reduction, which went from more than R$ 100 million in 2012, to around 20 million in 2022. It should also be noted that, over these years, contingency episodes were frequent, which often made the annual physical schedules of the mapping projects unfeasible.

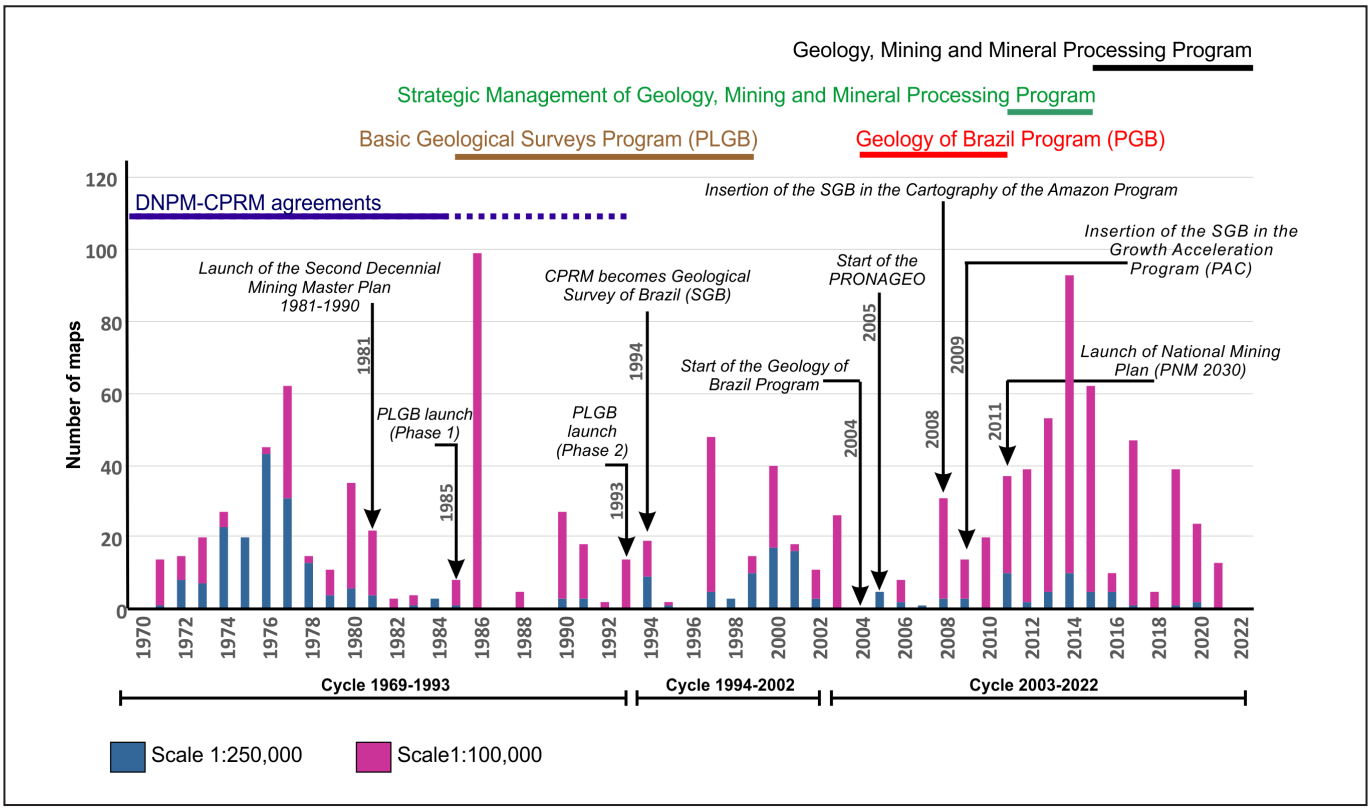

FIGURE 8. - Evolution of the number of geological maps published in the period of 1970-2022, with highlights of programs/actions over the time.

From 2012, the year following the launch of PNM 2030, until 2022, excluding the overlaps, that is, areas already worked in previous cycles, it was mapped around 405,000 km² of new areas in Amazon at the 1:250,000 scale, which represents an advance of 16% of achievement of the goal of PNM 2030, which forecast the mapping of 50% (approximately 2.5 million km²) of such territory between 2012 and 2030.

At 1:100,000 scale, a newly mapped area of around 10% of the Brazilian territory was advanced. If the PNM 2030 goal of mapping 60% of the non-Amazonian area (around 2 million km²) at this scale is considered, it can be said that 31% of the goal has been achieved by 2021.

The best performance of the evolution of the mapping at the 1:100,000 scale, in terms of the number of cartographic sheets, is due to the fact that the non-Amazonian territory was prioritized in the mapping campaigns, in virtue of better logistic conditions, if compared to the Amazon areas. Even in the Amazon, the areas mapped in such scale are located, in their majority, where there is better logistic infrastructure. Another important factor was the contribution of PRONAGEO in the performance of mapping at the 1:100,000 scale, prioritizing the Northeast and Center-South geoeconomic regions. Finally, Figure 8 shows the drop of the number of maps published in recent years, mainly due to the significant reduction of investments in geological cartography.

6. Considerations on the geological mapping in other Geological Surveys in the world

Most of the geological services of reference in the world emerged in the 19th Century, especially in Europe (e.g., Great Britain 1832, Portugal 1848, Spain 1851, France 1868, Russia 1882, among others), in addition to the USA (1879) and Canada (1842). Such movement continued in the early 20th Century, with the creation of other geological services, or equivalent institutions, such as in Argentina (1904), Brazil (*Serviço Geológico Mineralógico do Brasil*, 1907), Australia (1910) and China (1911).

In general, such institutions were conceived under the premise that it was the governmental assignment to develop the geological sciences and carry out thematic mapping (geological, mineral occurrences, soils, topographic, hydrological, etc.), required for the development of the industry, mining, agriculture, and for the planning of regional development.

Until today, geological mapping is considered a governmental assignment worldwide, the responsibility of the national and/or state/provincial geological services. However, the role of geological services as generators and providers of geoscientific information is changeable. The focus of geological cartography is also dynamic over time, due to demands or specific needs of the society and strategic aspects (economic, environmental, geopolitical), also being influenced by technological advances, and the geological knowledge itself, which may demand the revision and update of historical maps, when prepared under geological and technical concepts considered outdated.

The general context of the geological mapping in some countries is briefly presented, taking for example nations with large territorial extension and/or mining tradition, or smaller countries that already have an advanced stage of coverage of systematic geological cartography. Part of the information presented was obtained by visiting the respective institutional websites, and it is not always possible to discuss the percentage of coverage of geological mapping of the countries because such information is not accessible.

6.1. United States of America (USGS – United States Geological Survey)

The United States Geological Survey - USGS was created in 1879, with the purpose of "classifying public lands and examining the geological structure and mineral resources, inside and outside the national domains". Geological mapping has always represented a paramount activity, but it was in 1992, with the perception of the reduction of the geological surveys in previous decades, and with the awareness of its fundamental role in all basic and applied geoscientific investigations, which the US Congress enacted the National Geological Mapping Act (Public Law 102-285). Through this act, the National Cooperative Geologic Mapping Program (NCGMP) established the cooperation between USGS, State geological services, and American universities, aiming at the sum of efforts and responsibilities to promote the advancement of the basic geological knowledge of the country.

The National Geological Mapping Act was re-enacted in 1997, 1999, and 2009, with the last act effective in 2018. In the decennial plan 2018-2027, the NCGMP provides the creation of an integrated three-dimension digital geological map of the USA, to meet the needs of the country until 2030. Figure 9 shows the coverage of geological mapping of the USA at 1:250,000 and 1:100,000 scales, being possible to observe that the country also presents extensive domains without mapping coverage.

6.2. Canada (GSC – Geological Survey of Canada)

The Geological Survey of Canadá - GSC was founded in 1842 as one of the main governmental organizations of the country, and the first geological map of Canada was completed in 1864. The geological mapping led to many mineral discoveries, making the country one of the world's leading producers.

In the 2000s, from the perception that geoscientific exploration is the key to discovering new potential areas and that large extensions of the North of the Canadian territory still had insufficient geological knowledge, the Geo-Mapping for Energy and Materials (GEM) Program was launched by the Canadian government, with investments around US$ 200 million between 2008 and 2020, and more recently the GEM GeoNorth program was created (2020-2027). The projects are carried out through collaboration with the academy, research institutions, territorial and provincial geological services, and with the participation of institutions and indigenous people of the North of the country (GSC 2022).

6.3. Australia (Geoscience Australia)

The history of Geoscience Australia dates back to 1910 when the Australian Survey Office was established. Its current structure resulted from the merger, in 2001, of the Australian Geological Survey Organization (AGSO) and of the Australian Surveying and Land Information Group (AUSLIG) (Geoscience Australia 2022). The country also counts on State geological services, sometimes even older (e.g., Victoria 1852, Western Australia 1888).

The geological surveys were made in a large part of the territory in the first half of the 20th Century, especially produced by the State geological services, boosted by the search for oil and ore deposits, and by the expansion of the Australian mineral industry. The territory has significant coverage at the 1:250,000 scale, and the mapping at the 1:100,000 scale is ongoing, with about 30% performed until 2019. A strength of the Australian geological services is that they have the custody of the geological mapping products carried out by the private sector, which speeds up the coverage of the mapping, in addition to optimizing costs.

6.4 Spain (IGME-Instituto Geológico y Minero de España)

The *Instituto Geológico y Minero de España - IGME* began its history with the creation of *Comisión para la Carta Geológica de Madrid y General del Reino*, in1849. In 1910, it was called *Instituto Geológico de España*, and in 1927 it received the current designation (IGME, 2022).

The country is fully mapped at the 1:50,000 scale, including insular territories (Figure 10). Three series of mapping in 1:50,000 scales have been carried out, the first taking place from 1926 to 1970, the second between 1971 and 2003, and the third is in progress, as well as the preparation of cartographic sheets at the 1:200,000 scale is ongoing in the continent, and 1:100,000 in insular areas.

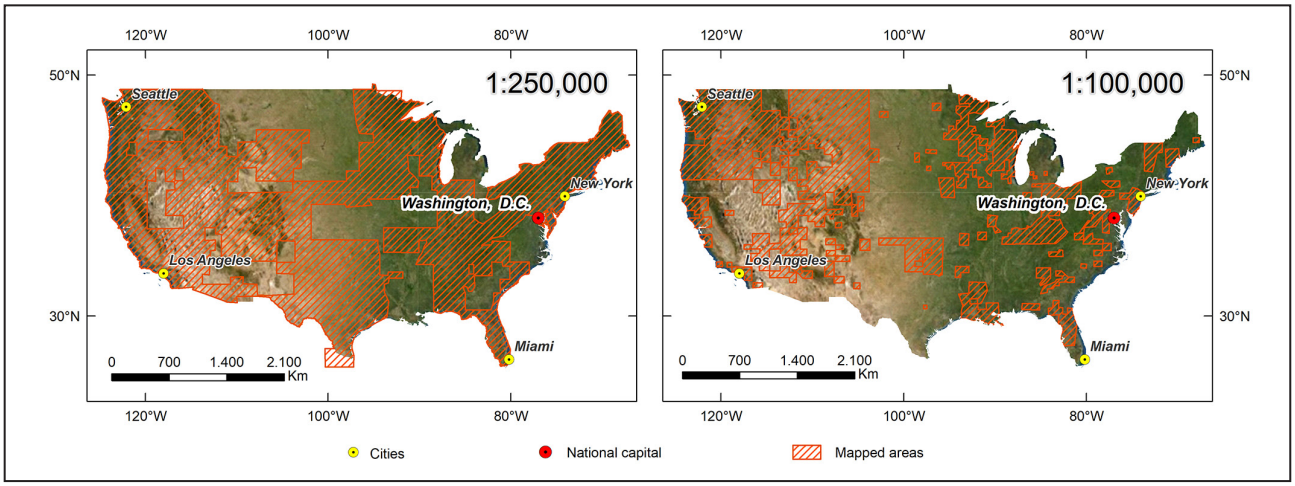

FIGURE 9. Coverage of the geological cartography at the 1:250,000 and 1:100,000 scales of the United States of America. Source: USGS, https://ngmdb.usgs.gov/mapview. Reference in March 2022. (USGS 2022)

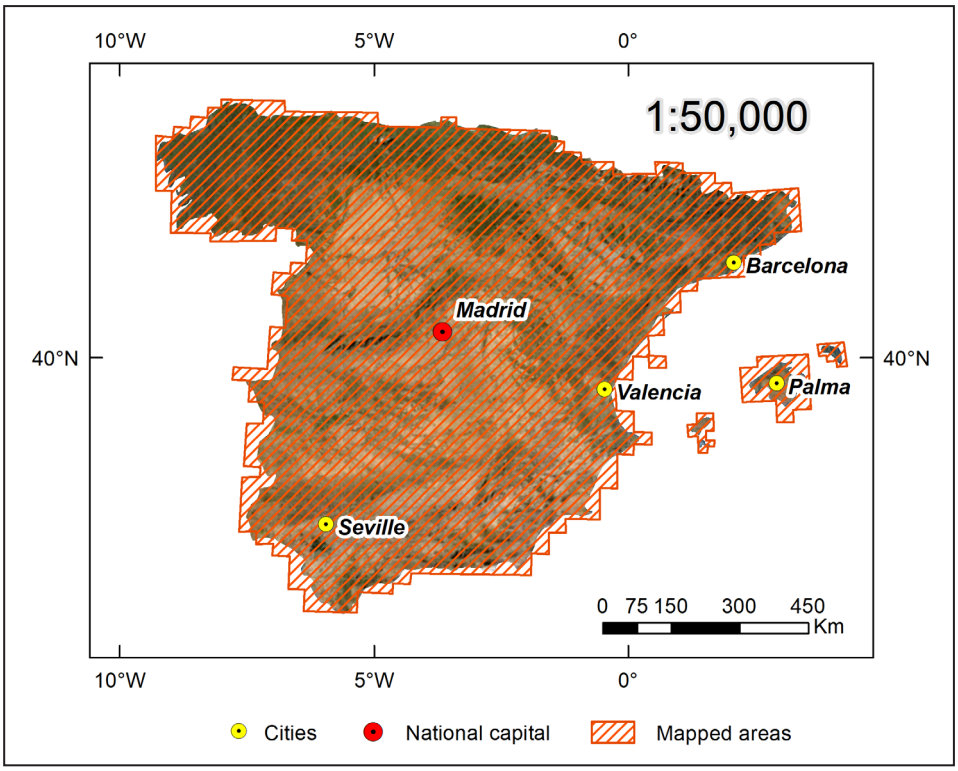

FIGURE 10. Coverage of the 1:50,000 geological cartography in Spain. Source: Zarza 2021.

6.5. Argentina (Servicio Geológico Minero Argentino--SEGEMAR)

The *Servicio Geológico Minero Argentino* - SEGEMAR was constituted in 1996, but its history started in 1904, with the creation of the *División de Minas, Geologia e Hidrologia*, with the purpose of making geological, mineralogical, and hydrogeological explorations, especially in the research of mineral fuels and thermal sources (SEGEMAR 2022). The SEGEMAR's current cartography schedule is based on Law 24,224 of Mining Replanning, of 1993, which declares that the State is responsible for geological and thematic cartography of the country (geomorphology, geophysics, metallogeny, gems and industrial minerals, geological risks, etc.), and defines the development of the *Programas Nacionais de Cartas Geológicas e Temáticas*. Through this program, more than 50% of the continental territory was mapped at the 1:250,000 scale, while surveys at the 1:100,000 scale are still in the preliminary phase (Figure 11).

6.6. Mexico (SGM - Servicio Geológico del México)

The Mining Law, enacted in 1992, constituted the *Servicio Geológico del México* - SGM as a decentralized public body, bound to the Secretariat of the Economy, and defined the set of assignments and responsibilities of the SGM, including the provision of geological information and updating of the geological mapping of Mexico (SGM, 2022). The geological cartography in the SGM is linked to the *Infrastructure de Información Geológico-Minera* Program. Since 1995, a great part of the works focused on the creation of the basic geological infrastructure of the national territory, at the 1:250,000 and 1:50,000 scales. The country is currently in an advanced stage of geological cartography, being since 2005 completely covered by cartography at the 1:250,000 scale, and with around 50% of the territory mapped at the 1:50,000 scale, in the period from 1995 to 2021 (Figure 12).

6.7. General comments

Although it has not been possible to access detailed information, it is clear that the beginning of the 1990s represents a phase of geological effervescence in the American continent, and of perception of the importance of the basic geological surveys as a strategy of development, not only for the mineral sector, but also with a fundamental role to subsidize investigations applied to the environmental management and physical space planning.

In this decade, the National Geological Mapping Act (1992) was enacted in the USA, the Mining Replanning Law (1992) in Argentina, and the Mining Law (1992) in Mexico. Brazil sought to follow this movement, since in such same period was enacted the Decree 917 (1993), which approved the Basic Geological Surveys Program (PLGB-Programa de Levantamentos Geológicos Básicos), and Law 8,970 (1994), which transformed CPRM into the Geological Survey of Brazil, having among its main assignments to perform the PLGB.

It should be noted that the continuity of the basic geological mapping programs over the last three decades in other countries was important to promote significant advances in mapping coverage, which resulted, for example, in the mapping of 100% of the Mexican territory and of more than 50% of Argentina at the 1:250,000 scale.

The general evaluation of the development of the basic geological cartography in the mentioned countries allows us to say that the coverage and the level of detail of the mapping vary according to the historical tradition, territorial dimension, stage of economic development, budget for geological

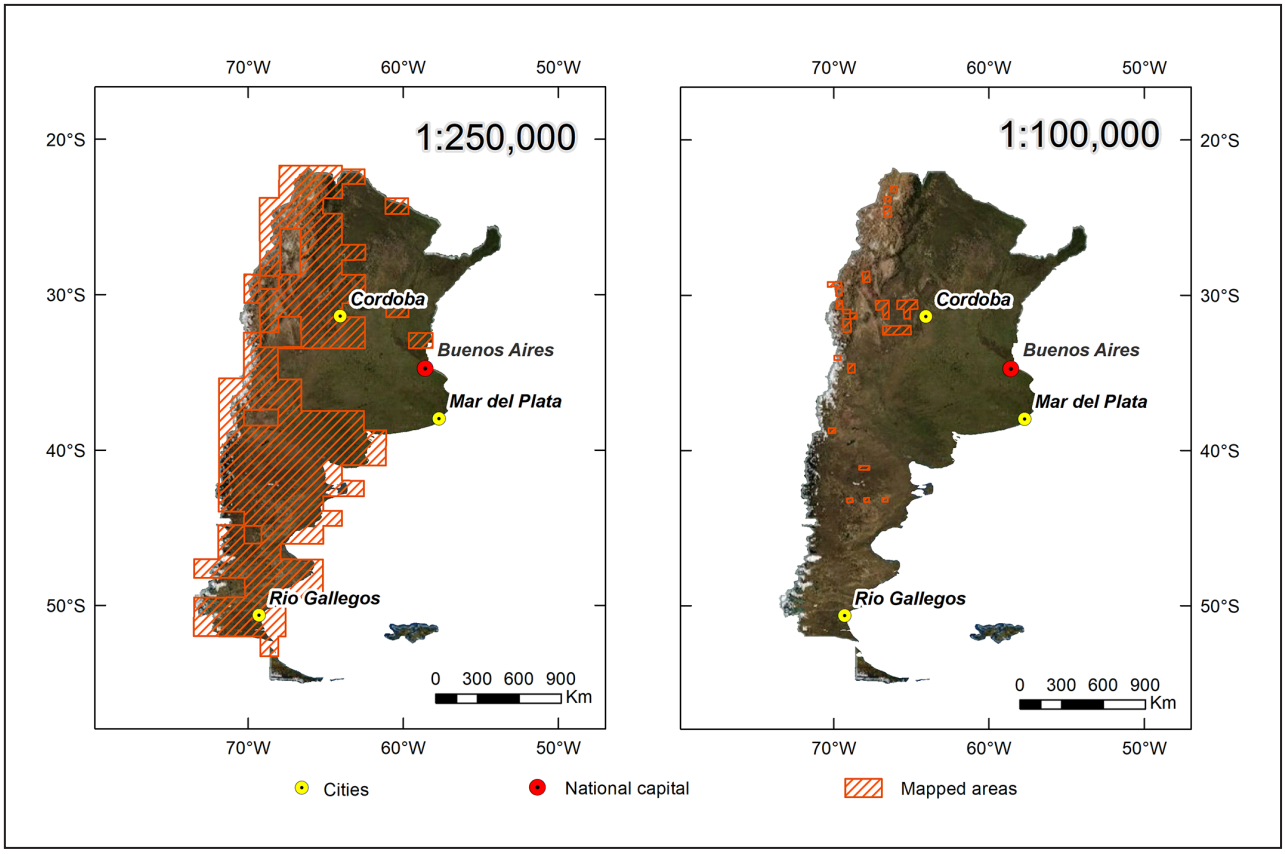

FIGURE 11. Coverage of the 1:250,000 and 1:100,000 geological cartography of Argentina (Gonzálvez 2021).

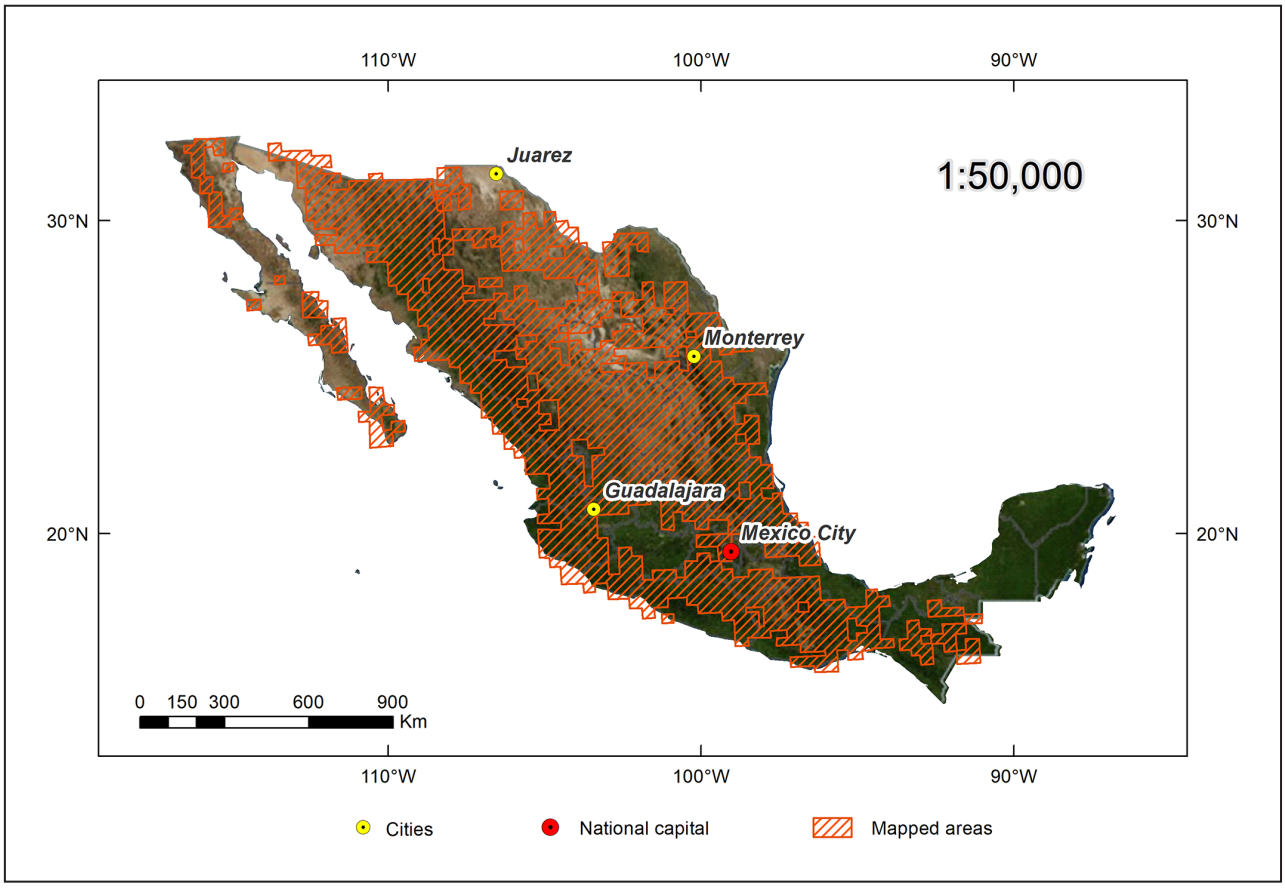

FIGURE 12. Coverage of the 1:50,000 geological cartography of Mexico (Montiel 2021)

research, continuity of the initiatives and programs, and of the sharing of responsibilities between Federal and State governments, and universities.

7. Final remarks

Brazil fits the profile of a country with a large territorial dimension, with an extensive continental margin, rich in non-renewable natural resources (energy, metallic, industrial, aggregated, and others) and (hydrological) renewable resources, affected by natural disasters (especially floods and landslides), and which also has the largest area of rainforest on the planet.

The evaluation of the performance of the geological mapping in Brazil over three cycles of mapping occurred between 1969 and 2022 shows that, although great efforts have been made, the country has still a great deficit of geological knowledge, with only 48% of its territory mapped at the 1:250,000 scale, and 27% at the 1:100,000 scale.

In addition to the challenge of mapping a country with more than 8.5 million km² and presenting very heterogeneous geoeconomic contexts, other factors contribute to such a scenario, including the discontinuity of initiatives and governmental programs, which directly impact the planning, the budget availability, the capacity of investment in human resources and infrastructure, and in the establishment of partnerships.

This work evidenced that, over 53 years under analysis, the periods of greater productivity and faster progress in geological mapping in Brazil were a consequence of well-defined governmental guidelines, proper investments, and sharing of responsibilities with State governments and through partnerships with the universities. Similar examples are seen in countries that have realized the importance of basic geological surveys as a development strategy.

It is expected that the information and discussions presented in this work support reflections and the definition of public policies and strategies aimed at the speed-up of the geological mapping in the country, from the perspective that knowledge is also a matter of sovereignty.

In this context, the beginning of a new cycle of geological mapping is suggested, with the incorporation of new technologies and improvement of processes that impact on the quality and productivity of the mapping, with sharing of actions and responsibilities through strengthened partnerships, aiming to maximize efforts and optimize resources, and with efficiency in the organization, storage, and accessibility of the acquired data and information.

It is mandatory that the new cycle be developed from the perspective that the Brazilian society shall be the main beneficiary, since it is not enough to justify investments in geological surveys to serve specific economic segments. The results of the mapping shall be, in fact, applied in other derivative activities that promote social welfare, such as, in the research to increase the water availability in Brazilian semi-arid regions, in the search for agricultural supplies that guarantee food security for the population, in the discovery of technological minerals that are essential to the energy transition and use of more sustainable sources of energy, and in the definition and implementation of public policies that promote the sustainable development of Amazon.

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Authorship credits

Author	A	B	C	D	E	F
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VCM		■	■	■	■	
FPSLA			■		■	
VRSS			■		■	
ELK				■	■	

A - Study design/Conceptualization **B** - Investigation/Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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