MINERAL EXPLORATION IN BRAZIL

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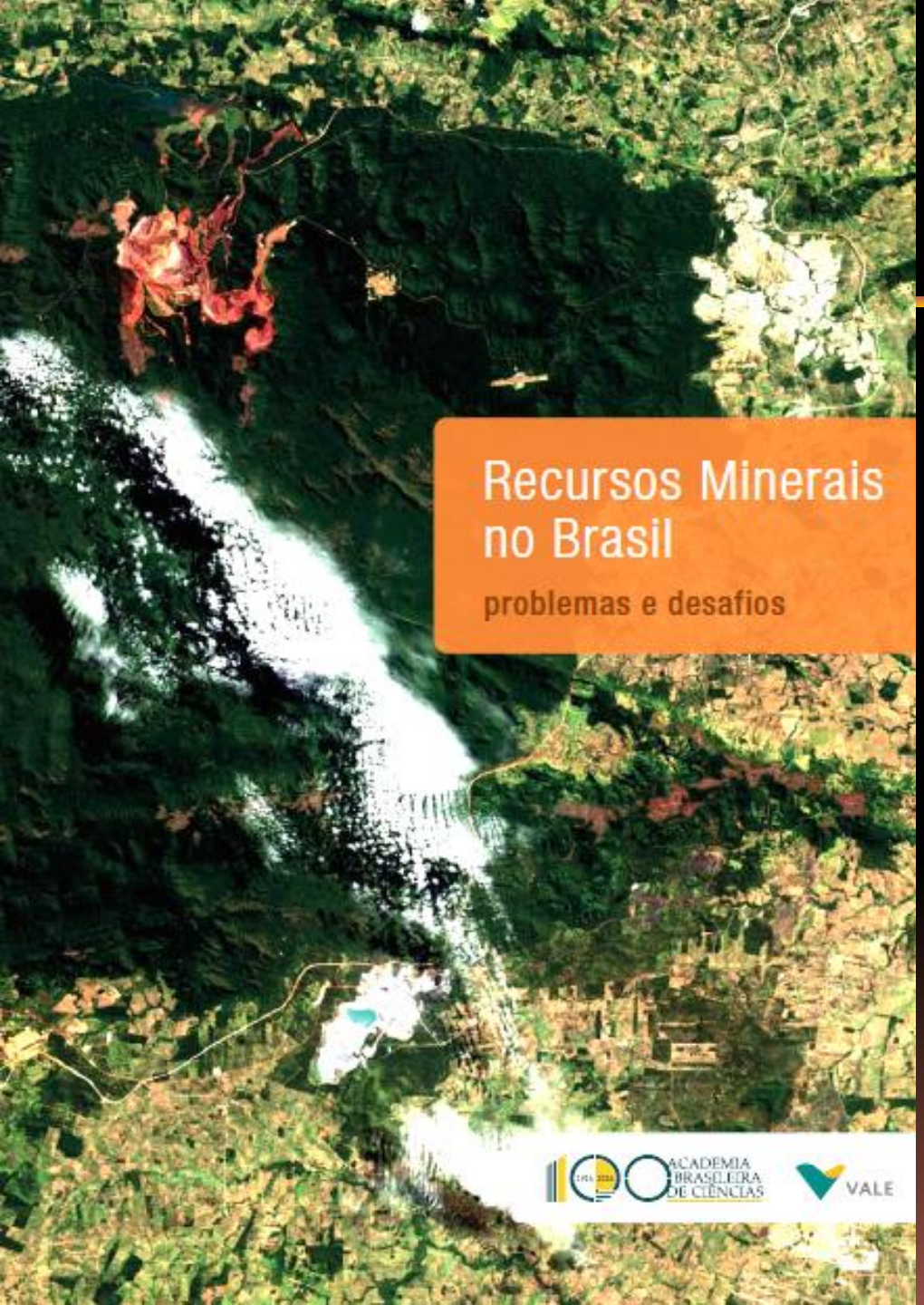
24th World Mining Congress
MINING IN A WORLD OF INNOVATION

VALE



Chapter II

Mineral Exploration in Brazil

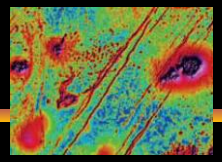
Mineral exploration in Brazil: use of ore deposit models and mineral systems
(Bettencourt, J.S.; Juliani, C.; Monteiro, L.V.S.)

Remote sensing in mineral exploration in Brazil
(Crósta, A.P.; Almeida, T.I.R. de; Paradella, W.R.; Silva, S.M.P.; Meneses, P.R.)

Geophysical prospecting in Brazil
(Cordani, R.)

Geochemical prospecting in Brazil
(Licht, O.A.B.; Angélica, R.S.)

Data integration & mineral exploration
(Souza Filho, C.R.; Silva, A.M.)



Mineral Exploration in Brazil

The purpose of this chapter is to discuss:

The historic use of the mineral deposit models, in mineral exploration in Brazil;

The modern concept of mineral systems, still poorly used in the mineral exploration in Brazil;

The critical analysis of the factors responsible for the probability of mineral exploration success, in Brazil;

The systematic application of geotechnologies, and data integration via 2D -3D models;

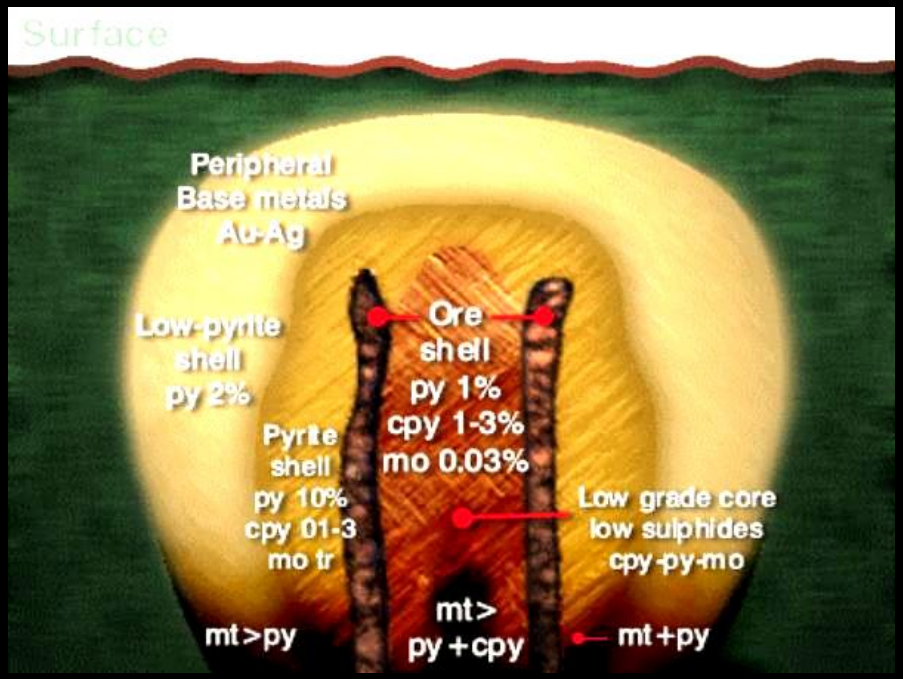
The constraints to the gathering of mineral exploration information;

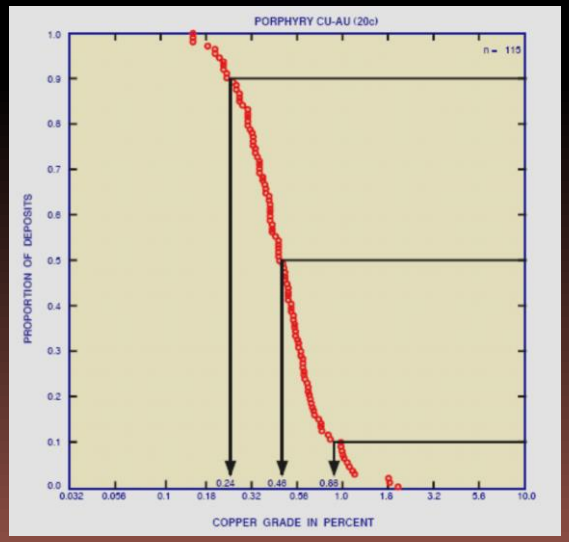
The role of basic geology, geological processes, and creativity of exploration staffs;

The importance of the scientific knowledge for the Mineral Exploration;

Future trends and implications.

Ore deposit models





Form a continuum and are divided into two end members:

Empiric model (factual observation): based on observational geological data, including grade-tonnage data, forms the basis for exploration programs

Genetic or conceptual model, based on theoretical concepts deals with the identification of processes (ore genesis)

Descriptive, genetic and financial models are used as the primary tools for planning exploration strategies

Cox & Singer, (1986); Thompson, (1993); Henley and Berger, (1993), Bliss & Menzie (1993)

Other ore deposit models

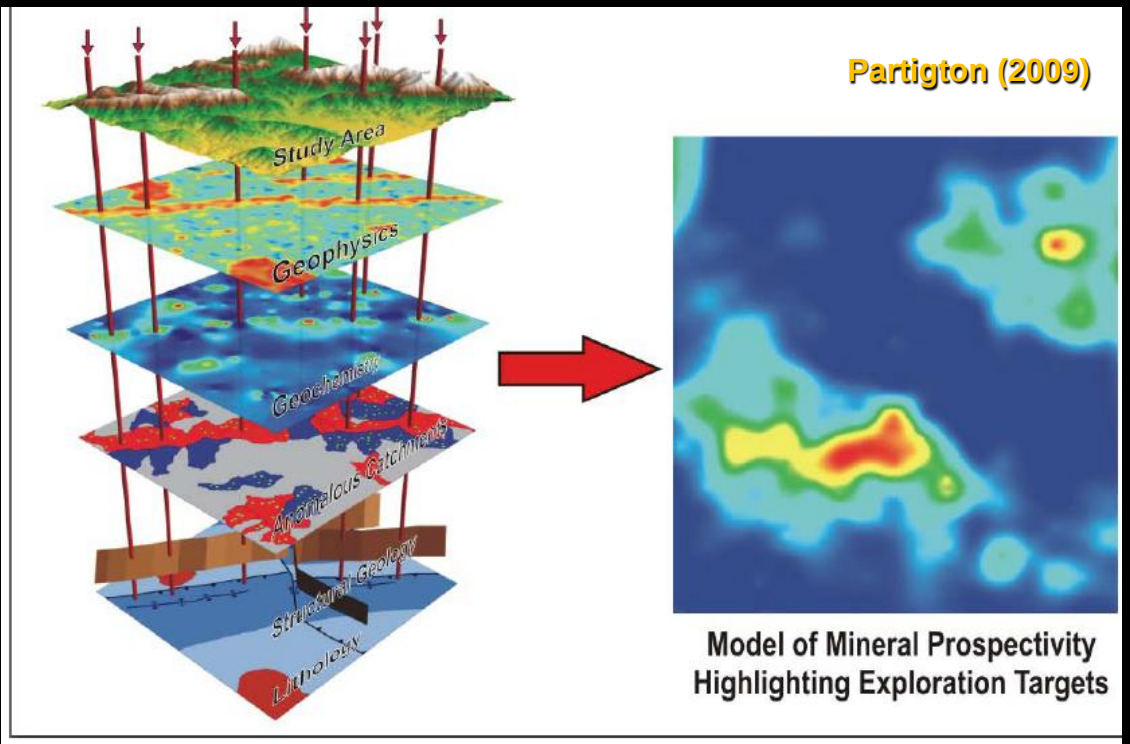


Figure 1 Types of mappable geological data used to target mineral exploration.

Spatial mineral deposit models

Grade and tonnage models

Characteristic models

Quantitative of processes models

Methodological models

Financial models

Exploration models

Use of artificial intelligence and neural networks for metallogenetic analysis

Use of geoprocessing for the definition of mineral availability, evaluation, and for the probability of mineralization in the analyzed areas

Cox & Singer, (1986); Thompson, (1993); Henley and Berger, (1993), Bliss & Menzie (1993)

The concept of Mineral Systems: application to metallogenesis

A distinct conceptual approach for the understanding of the genesis and exploration of mineral deposits;

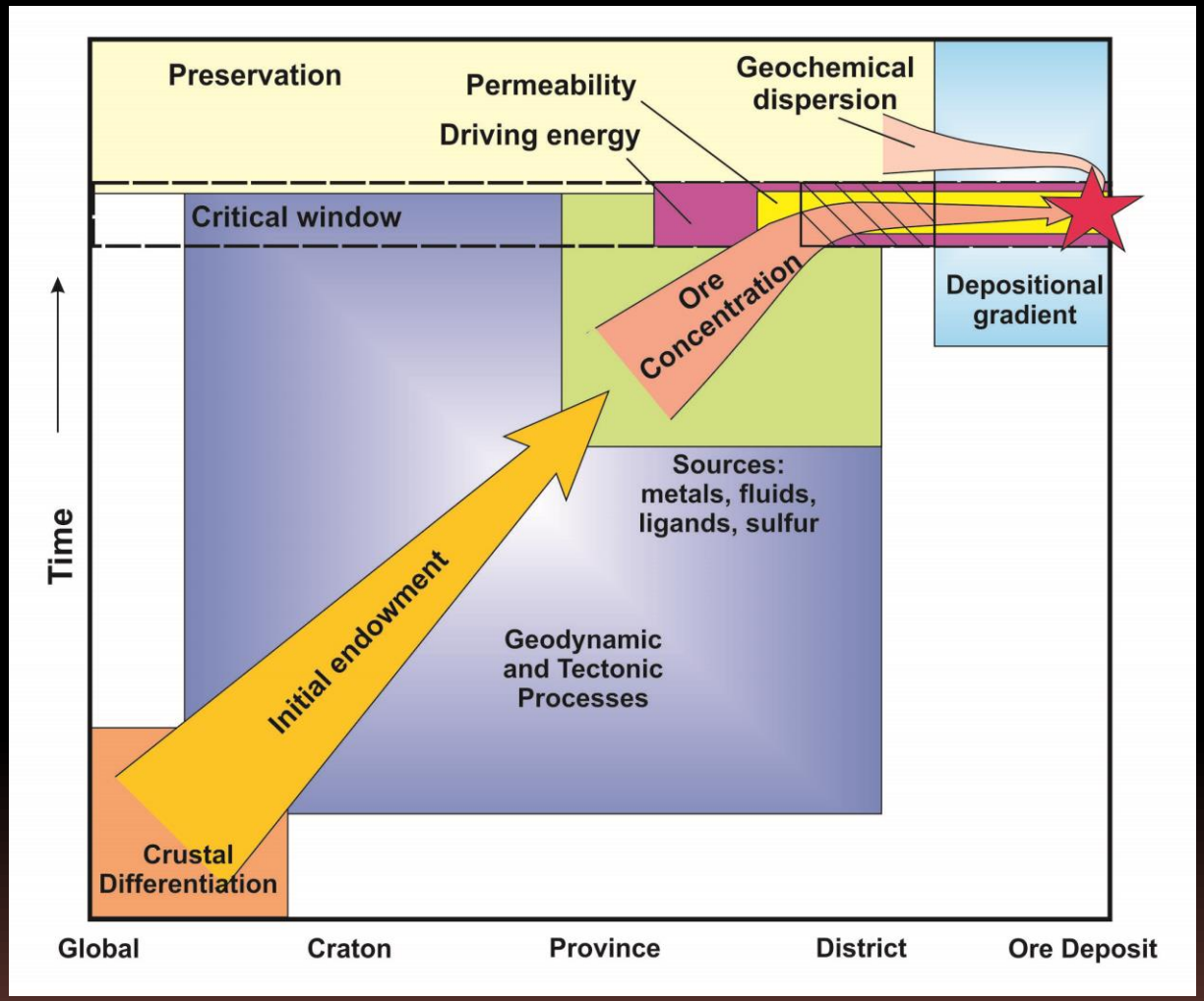
The concept differs from the genetic model counterpart: the focus is on the attributes or processes at multiple scales (even continental), but not at the deposit scale;

The deposit attributes are controlled by tectonic processes, which result in the formation and evolution of a geologic/geotectonic province;

The mineral deposit represents a local expression of the wide mineral system operating at different scales, with focus on energy and mass flux.

Wyborn et al, (1994); Knox-Robinson & Wyborn (1997)

Mineral System



Concept of mineral system and its relationship with spatial and temporal scales (GEOSCIENCE AUSTRALIA, 2013).

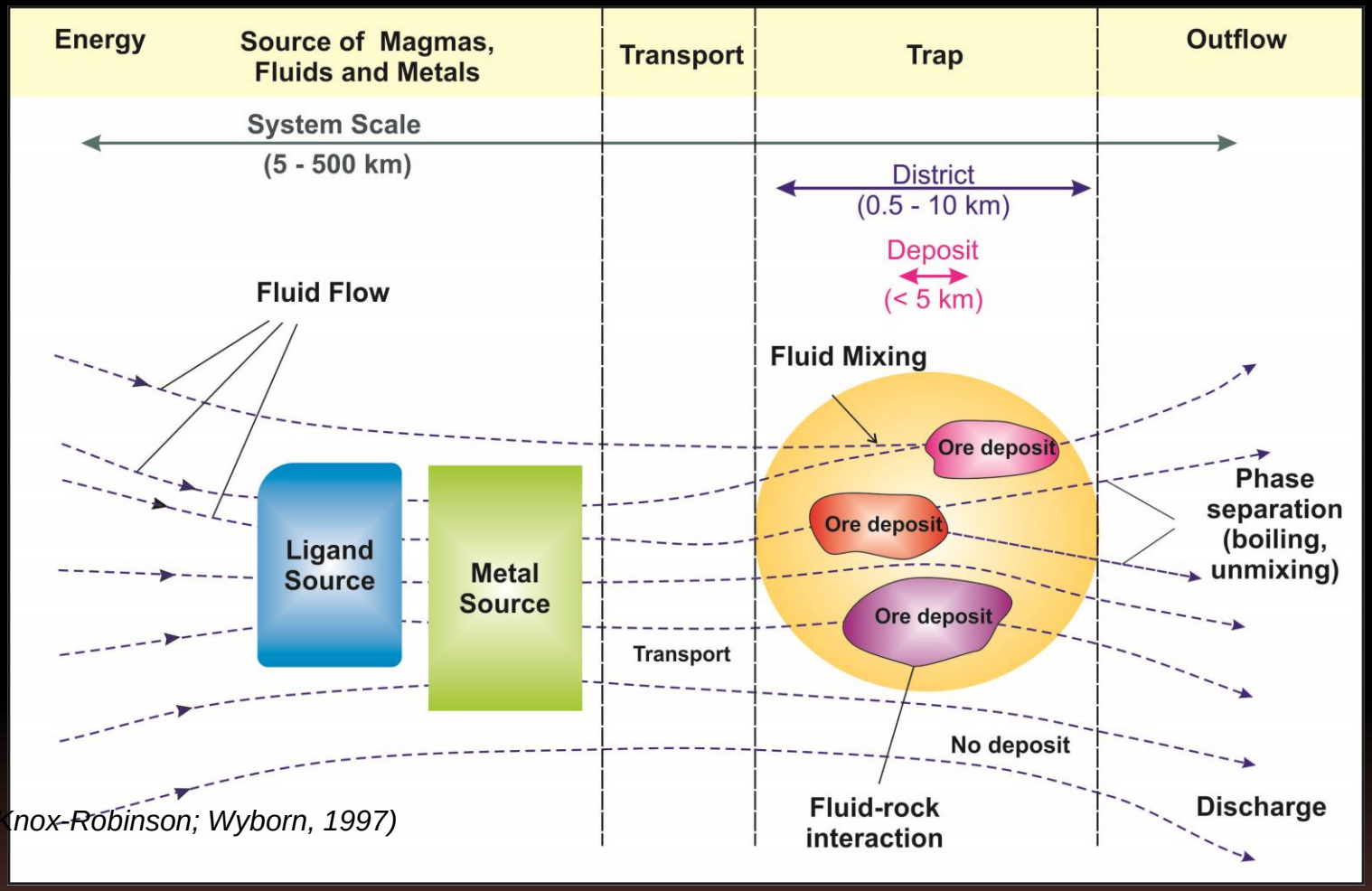
Ore deposits represent the foci of large-scale systems of mass and energy flux;

The way to predict the location or the metal endowment is to understand the entire system.

The system comprises a scale-dependent hierarchy of processes.

The largest observable scale of process is continental scale

Mineral System conceptual model and critical attributes



(Knox-Robinson; Wyborn, 1997)

Mineral systems and ore deposit modeling concepts are currently integrated for probabilistic analysis aiming at producing prospectivity, favorability and mineral potential maps in Geographic Information System (GIS).

(McCammon, 1993; Katz, 1991; Bonnham-Carter, 1994); (Kreuzer et al. 2008)

The importance of ore deposit models and mineral systems

Mineral exploration planning

Regional assessment of favorable areas

Access to mineral resources quantification and prediction

Key to unrecognized deposit types and features

The Mineral System approach permit the comprehension of processes responsible for inheritance, fertility, and metallogenetic specialization

Ex: Au epithermal; Cu-Mo porphyry; IOCG; magnetite-apatite deposits

Are key to economic analyses of resources

The models are never complete. We need better genetic and exploration models, as well the critical key features in exploration targeting and discovery

REMOTE SENSING IN MINERAL EXPLORATION IN BRAZIL

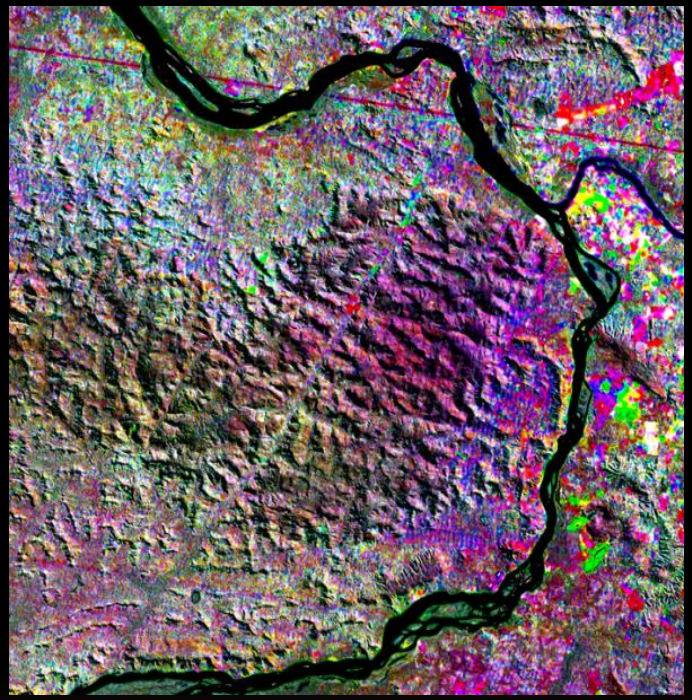
The state-of-the-art of remote sensing applied to mineral exploration is analyzed:

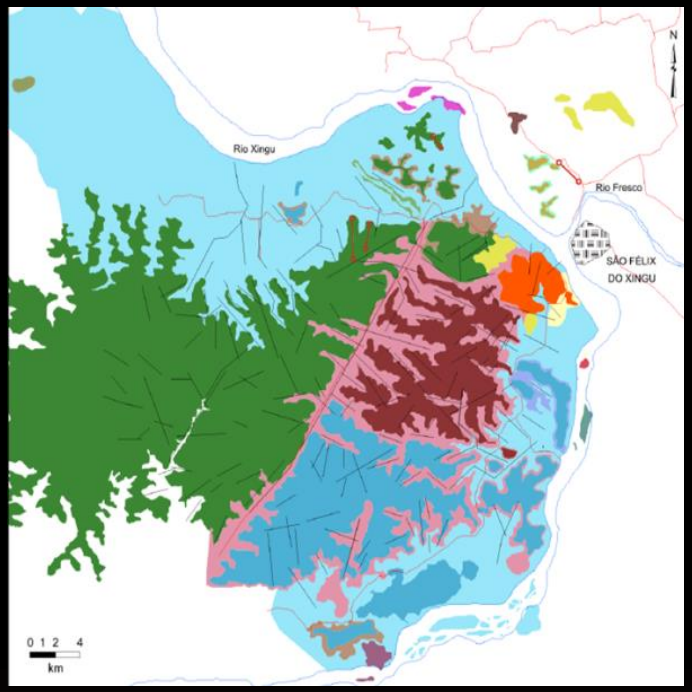
✓ Main technologies available, specifications, assessment of its use in Brazil by the academic and industrial sectors, potentials and limitations

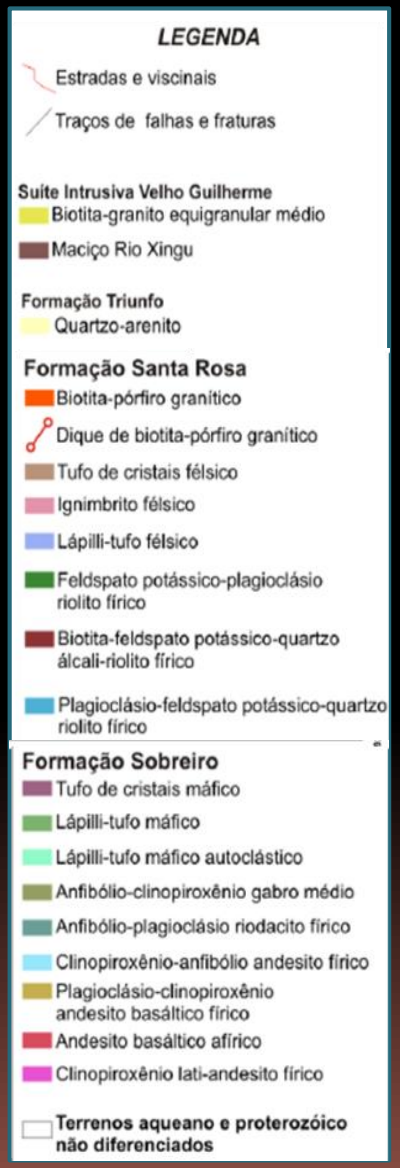
✓ Case studies developed and considerations about prospects of remote sensing for mineral exploration in Brazil are presented

Geobotany by Phenology in a Sequence of the Paleoproterozoic Uatumã Igneous Event, São Félix do Xingu, Pará

Case-study developed by Teodoro Isnard Ribeiro de Almeida (IG – USP)







Fernandes et al. (2011)

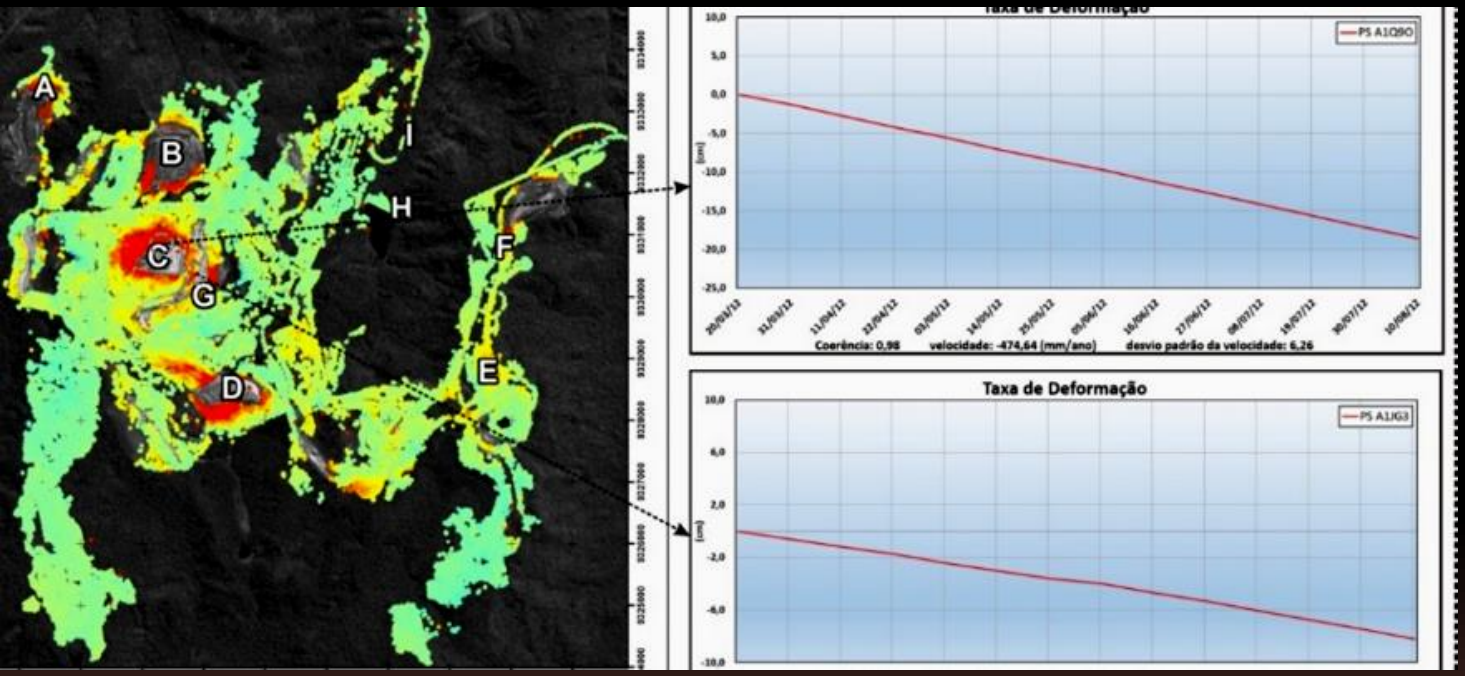
Correlation between the phenological variability of the vegetation and the volcanic units of the Sobreiro (calc-alkaline) and Santa Rosa (alkaline A-type) formations.

These units have hydrothermal alteration zones with evidence of epithermal high- and low-sulfidation Au-Ag-base metals in the Sobreiro Formation and low-sulfidation Au-Ag in the Santa Rosa Formation.

The technique allowed the identification of A-type sub-volcanic porphyry stocks, with potential for Sn and intrusion-related Au mineralization.

Monitoring Slope Stability in the Carajás Iron Mines With TerraSAR-X Using Differential Interferometry (DInSAR)

Case-study developed by Waldir R. Paradella[1], José C. Mura[1], Fabio F. Gama[1], Athos R. Santos[1], Guilherme G. Silva[1], Mauricio Galo[2], Paulo O. Camargo[2], Arnaldo Q. Silva[3] ([1] INPE, [2] UNESP, [3] IG-UFPA)



Spatial distribution of measurement points for the iron mines of the Serra Norte area using 14 TerraSAR-X images (23Mar-10Aug, 2012) showing the rate of deformation velocity (mm/year). Average density of 800 points/km^2.

Colors in the deformation bar show the direction of the movement: red = away from the sensor, meaning probably subsidence; blue = towards the sensor meaning probably uplift. Non-deformed areas appears mostly green. Deformed areas are shown as yellow-red and correspond to sterile waste dumps (marked as A, B, C, D and F) and bench slopes (G).

Monitoring Slope Stability in the Carajás Iron Mines With TerraSAR-X Using Differential Interferometry (DInSAR)

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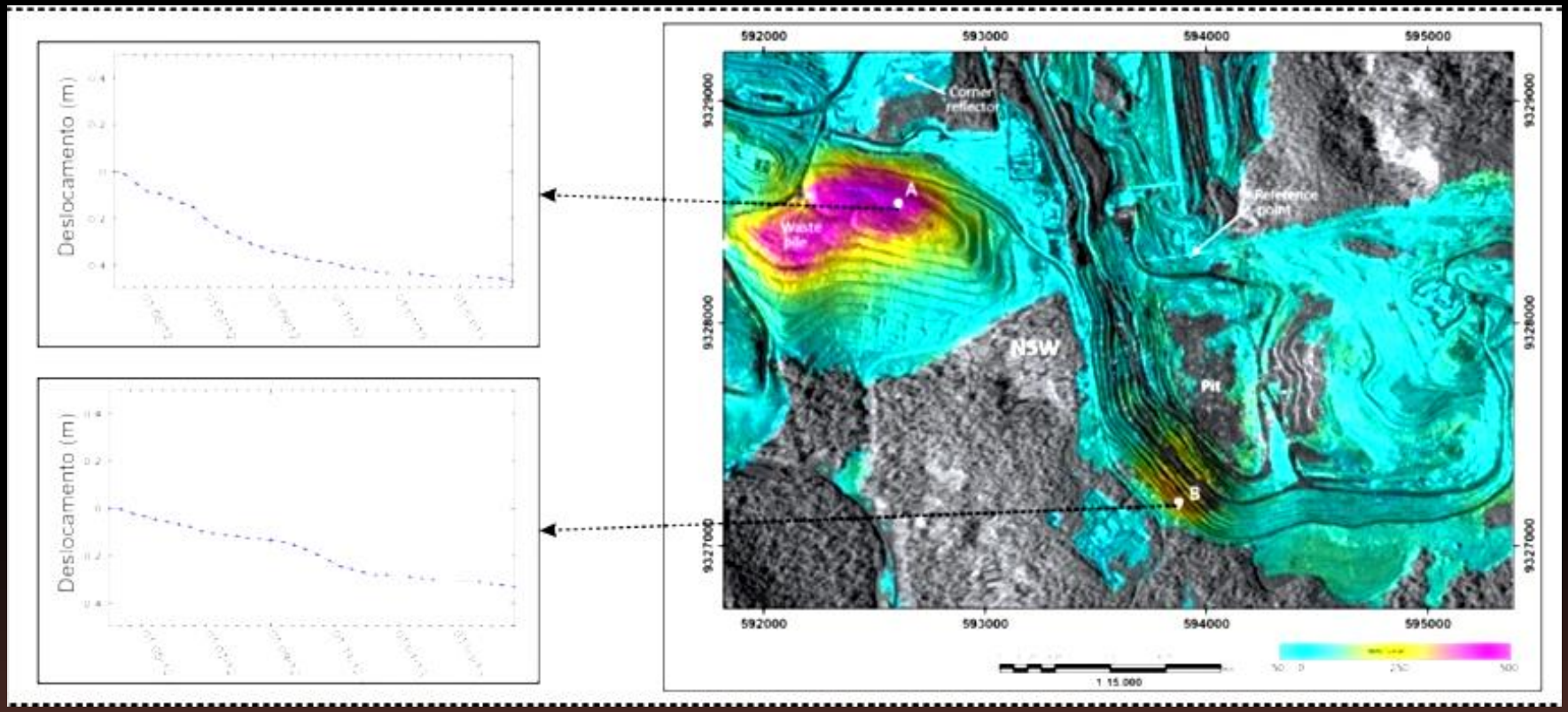
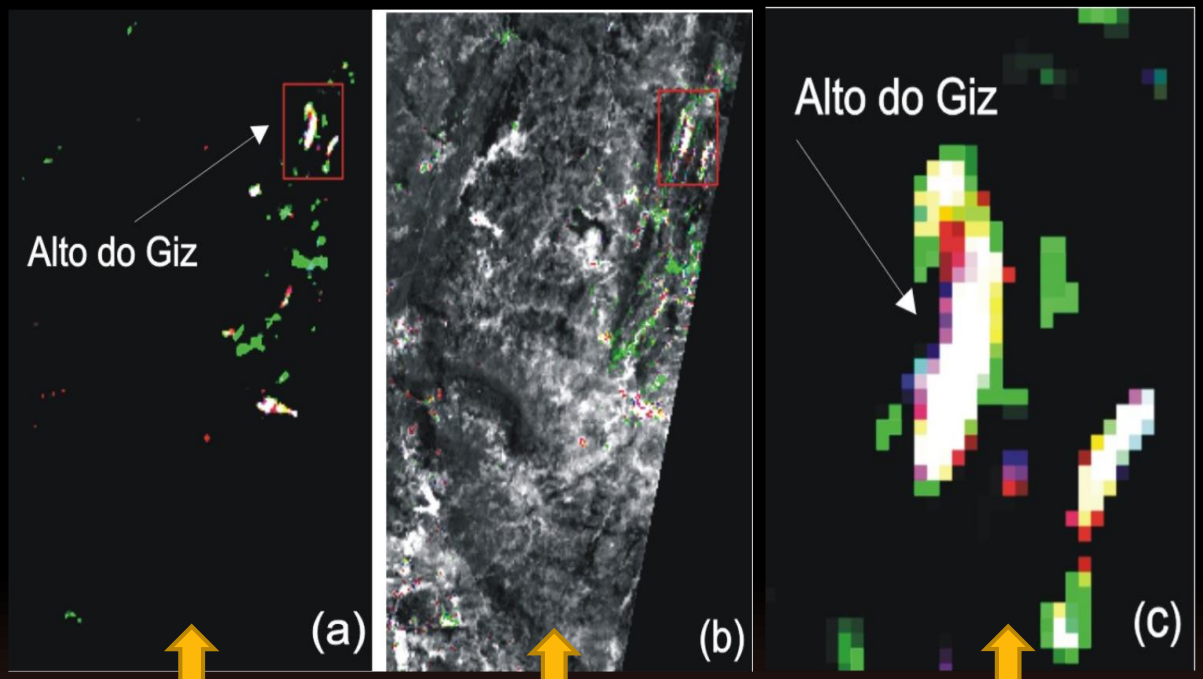
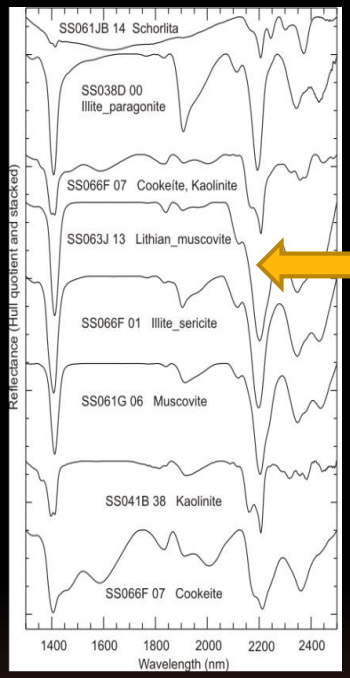


Sterile waste dump of N5W mine showing the deformation velocity (mm/year) using 33 images (20Mar-20Apr, 2013). Deformation/time sections correspond to measurement points of bench slope (upper section) and pit slope (lower section).

Spectro-mineralogical Characterization and Mapping of Granitic Pegmatites of the Borborema Pegmatitic Province

Case-study developed by Sebastião Milton Pinheiro da Silva (UFRN)





Reflectance spectra of pegmatite minerals in the 1.4 to 2.5 µm interval of the electromagnetic spectrum showing the main diagnostic absorption features.

Mapping of pegmatite and muscovite-quartzites of the Equador Formation

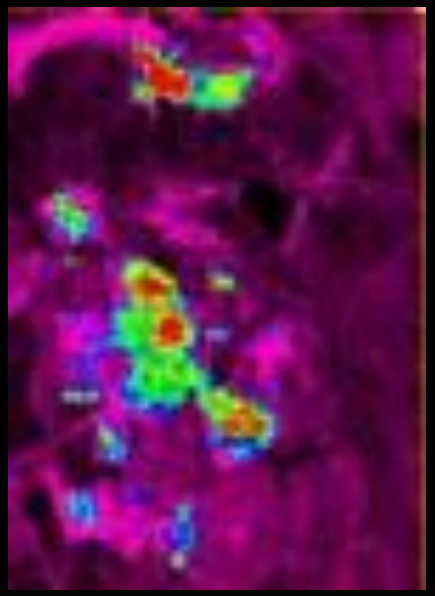
Previous image over a single-band image of the Hyperion sensor

Alto do Giz pegmatite:
Kaolinite = red
Muscovite = green
Paragonite = blue
White pixels all 3 minerals.

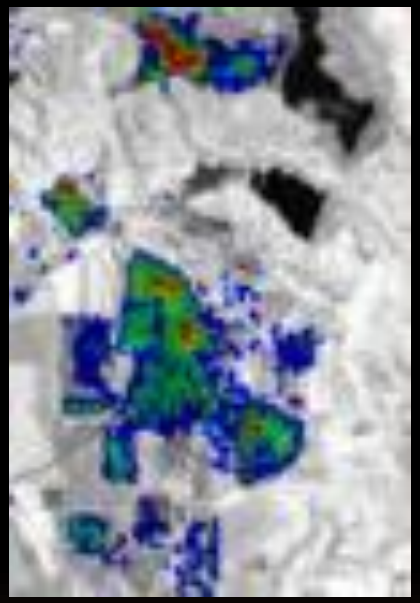
Detection of Phosphate Minerals Using ASTER Sensor

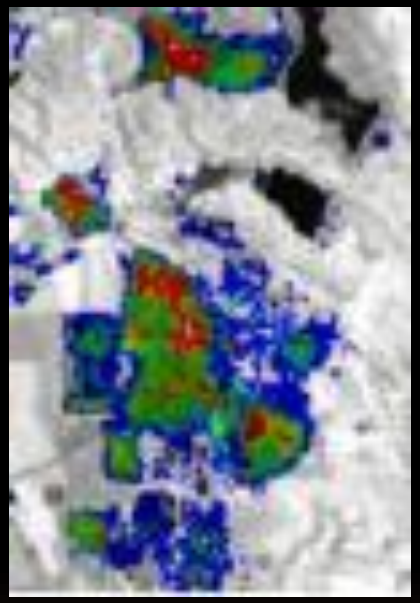
Case-study developed by Paulo Roberto Meneses & Gustavo Macedo de Mello Baptista (IG-UnB)

Catalão I, Goiás

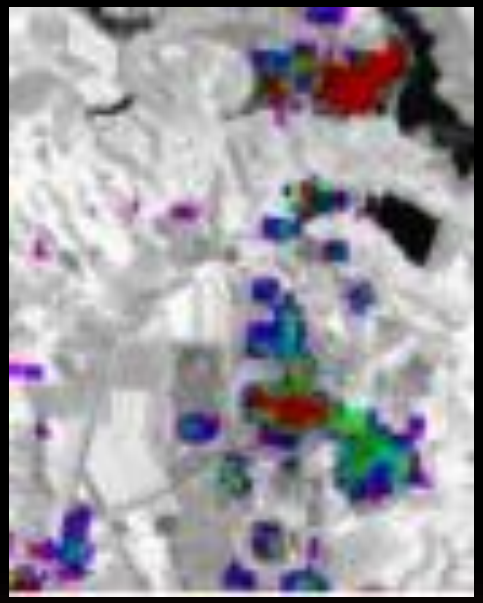


Visible/Near Infrared





Shortwave Infrared



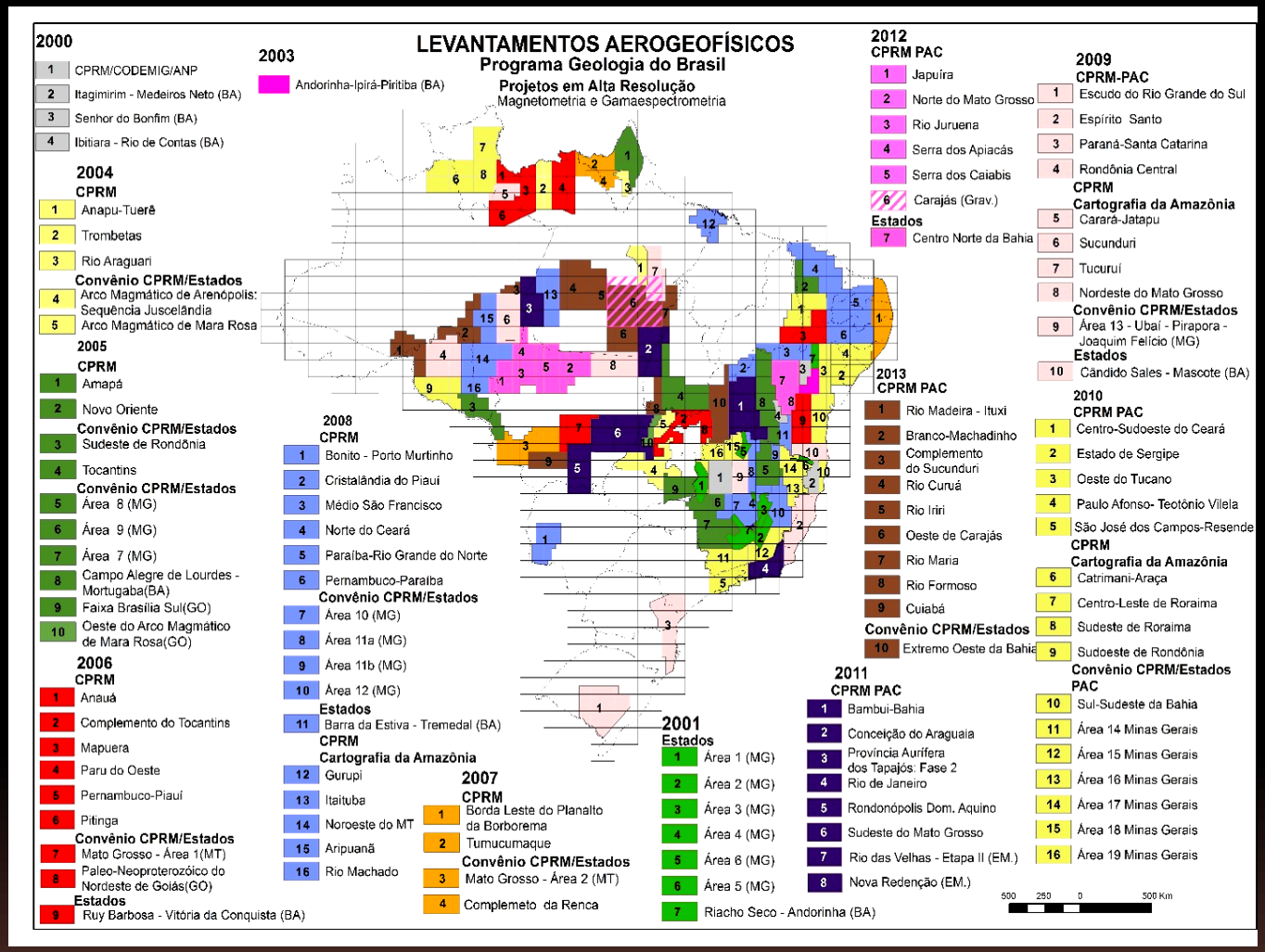
Thermal Infrared

From left to right: spectral classification of ASTER images corresponding to the minerals: Monazite; Flogopita-dolomite-hydroxilapatite; Apatite-dolomite; Apatite.

Geophysical prospecting in Brazil

- ✓ Geophysics is one of the powerful tools in modern Mineral Exploration;
- ✓ Geophysical methods are the same for decades, but the difference today is that the interpretation depends on variations in the physical properties of rocks “in site”, in a 3D environment;
- ✓ Integration with geological and direct drilling is mandatory;
- ✓ The integration of geophysical techniques, together with geology and multi-element geochemistry provides the best technical means of exploration success and of reduction exploration risks;
- ✓ There is no more anomaly map;
- ✓ Data is in inverted unit i.e. physical properties;
- ✓ Modeling and integration: direct drilling (confirmation) data is essential;

Brazilian High-Resolution Airborne Geophysical coverage up today



CPRM, (CODEMIG-MG, SIG-GO, CBPM-BA)

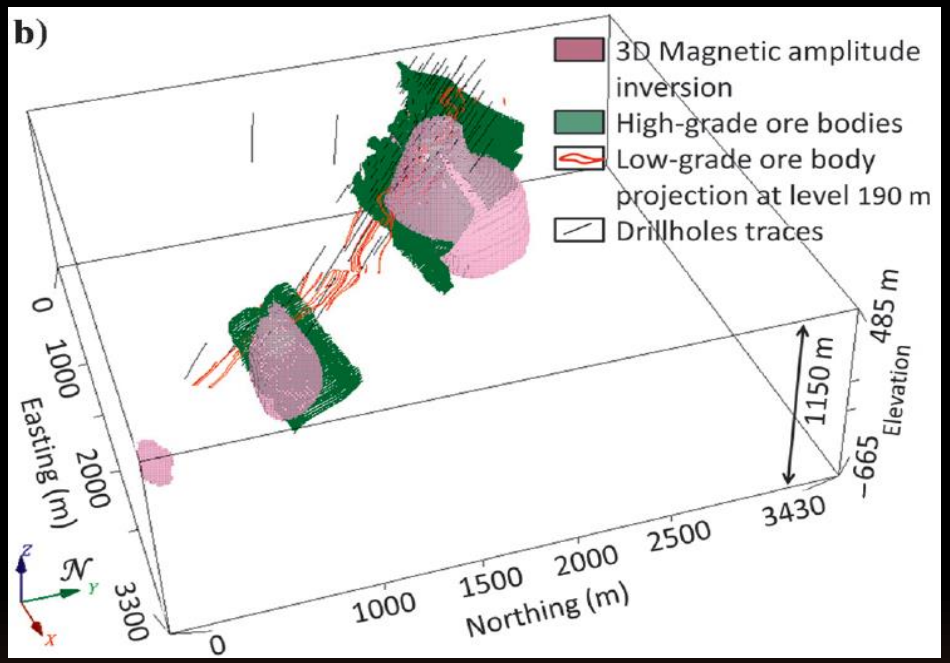
Spacing: < 500 m
Fly altitude: 100 m
Mag sampling: 10 Hz
Gamma: 1 Hz

Costa et al. (2011)

CPRM has recently flown virtually all prospective terrains with high resolution aeromagnetic and gamma-ray spectrometer surveys to lead to new opportunities for discovering economic mineralization. This is an important and necessary "first step" on application of Geophysics in Mineral Exploration.
It is expected that such huge amount of new data could bring new exploration discoveries.

Geophysical modeling

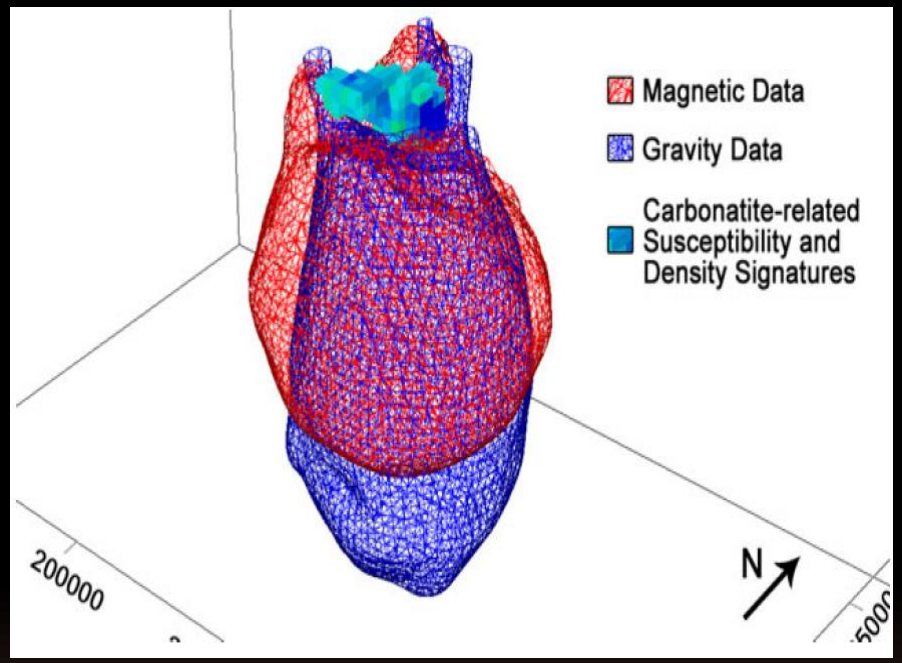
Furnas IOCG Deposit (Carajás Province, Brazil)



(Leão-Santos *et al*. 2015)

3-D correlation between obtained susceptibility models **(pink)** and the 3D geological model of high-grade mineralization zone **(green)** in the deposit Furnas

Catalão Deposit (Goiás, Brazil)

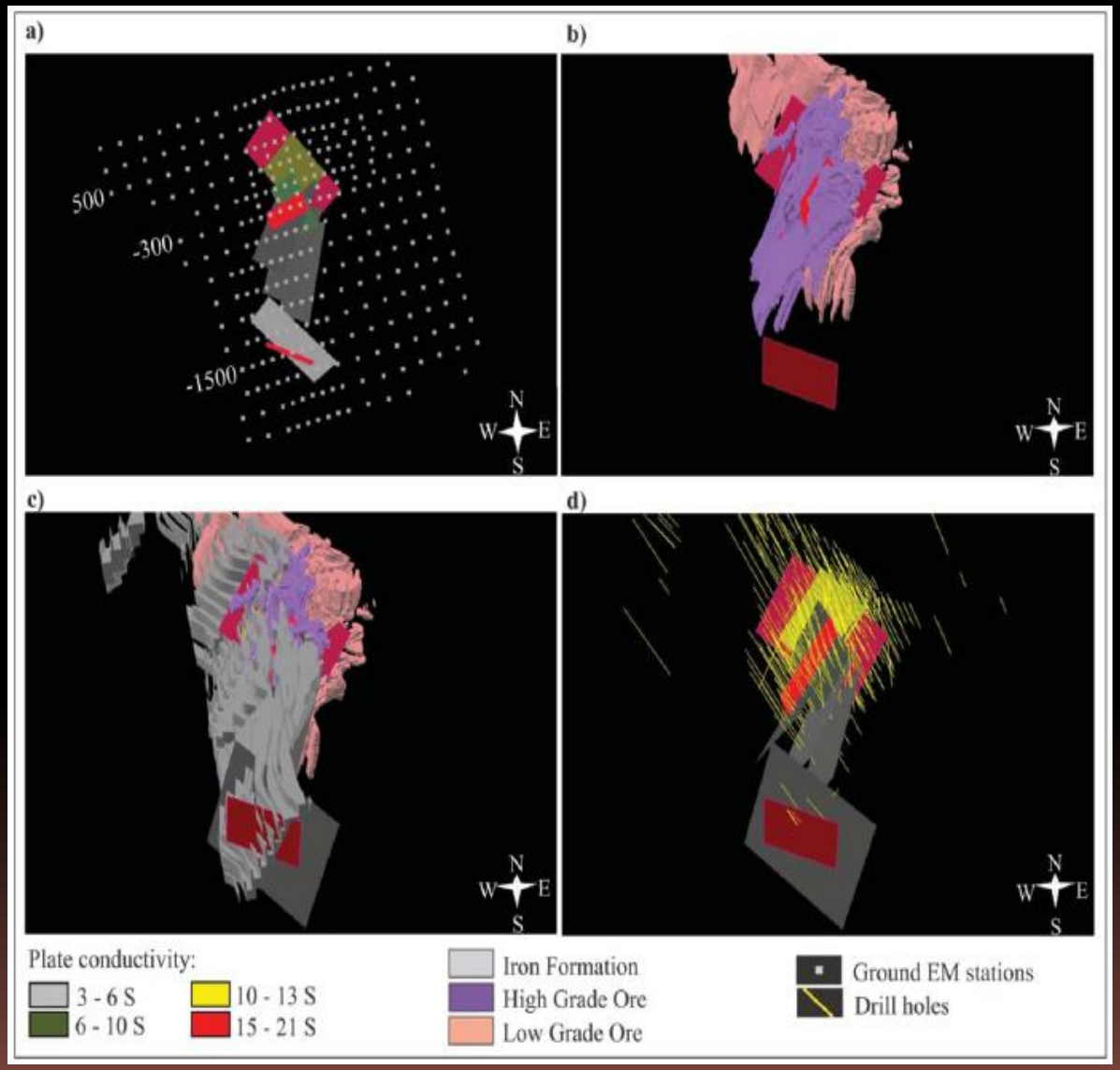


(Mantovani *et al*. 2015)

3-D visualization perspective of comparison between model densities **(blue)** and the magnetic template **(red)** of the Catalão alkaline complex. The solid top is interpreted as carbonatite model.

Cristalino IOCG deposit (Carajás)

EM field measurement position and modeled EM plates



Detailed inverted EM plates and high- and low-grade ore geological model

EM plates with high and low grade ore and iron formations

Inverted EM plates and diamond drill holes

Melo *et al.* (2014)

Geochemical prospecting in Brazil

Geochemical exploration methods have been widely used in Brazil, mainly for:

- ✓ Geological Mapping (mainly related to government agencies, e.g. CPRM, Geological Survey of Brazil)
- ✓ Mineral Exploration Projects, from private mining companies

Approximately amount of samples collected for geochemical exploration purpouses from diferent government agencies since 1970

	Stream Sediments	Heavy Mineral Concentrates	Soils
DNPM	11.281	-	50.000
CPRM (Geological Survey of Brazil)	≈ 115.000	-	-
MINEROPAR (Paraná State)	9.597	2.940	14.732
METAGO (Goias State)	30.375	-	-
CBPM (Bahia State)	13.758	541	83.894
ProMinério IPT (São Paulo State)	≈ 16.000	-	-

Some Examples of Mineral Deposits discovered in Brazil using Geochemical Exploration Methods

Cu-Ni ores related to ultramafic rocks (Goiás state)

Au in the Rio Itapicuru Greenstone Belt (Bahia State)

Cr from Campo Formoso (Bahia State)

Fe-Ti from Campo Alegre de Lourdes (Bahia State)

Pb-Zn from Fazenda Santa Maria, Minas do Camaquã (Rio Grande do Sul State)

Several Phosphate deposits, Bambui Group (Bahia, Minas Gerais, Goiás and Tocantins states)

Cu-Au deposits, Serra dos Carajas (Pará State)

Future Trends

Regional multipurpose and multi-methods Geochemical Exploration Projects

To help in the Geological Mapping

Mineral Deposit Exploration

Environmental and Health Issues

Low-density regional geochemical projects

in order to cover big areas with small amount of samples

(e.g. stream sediment sampling)

Very important for remote areas, like the Amazon region

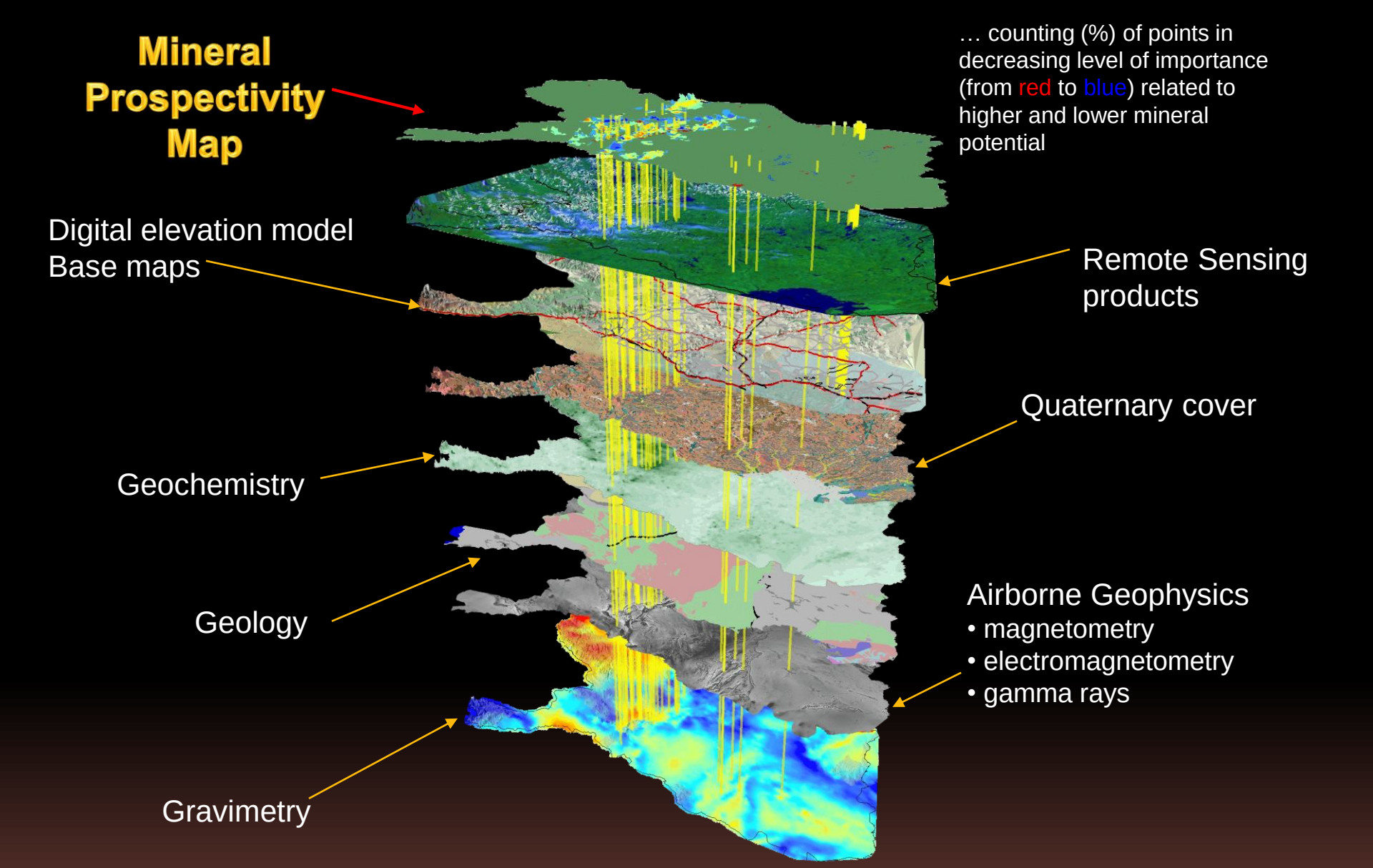
Integration of Geological Datasets for Mineral Exploration

The integration of digital data in order to define exploration targets in the continental, regional and district scale is a key activity for the progress of the global mining industry;

Numerous mathematical and statistical techniques and computer programs were developed, allowing efficient use of exploration datasets generated cumulatively by government and private companies;

The expansion of mineral exploration and mining have demanded the continued development of exploration techniques and aimed at reducing the cost and time invested in these activities;

This work aims to provide a synoptic view of evolution, state of the art and future trends in data integration focused on mineral exploration.

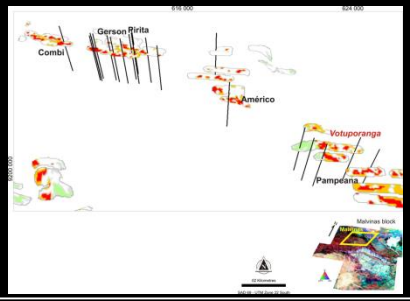


Datasets traditionally used in the generation of mineral prospectivity maps. In many countries, including Brazil, these data are made available by the Geological Survey to work on a regional scale. On this scale, one of the main goals of data integration is to significantly reduce the search area for a particular mineral deposit (adapted from Nykänen, 2008).

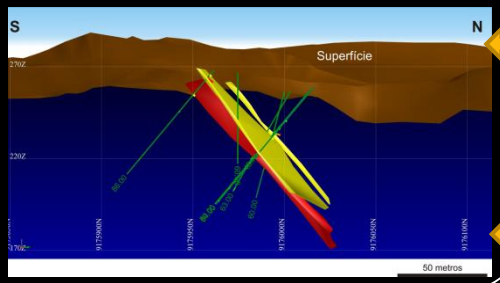
Systematics for the generation of mineral prospectivity maps

Prospectivity Model and Validation

Model



Validation

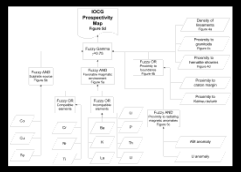


(v) model validation through drilling campaigns and detailed geochemistry

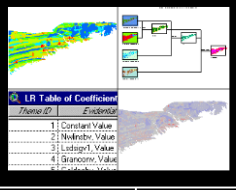
(iv) generation of the prospectivity map, substantially reducing areas and ranking them among those of highest and lowest priority for follow-up.

Modeling

Model



AcSDM

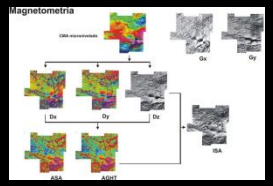


Fuzzy Logic
Logistic Regression
Weights of Evidence
Neural Nets

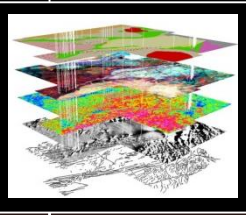
(iii) integration of evidential maps using mathematical models available in the Spatial Data Modeler software.

Processing and interpretation

Data Processing



Interpretation



Grids
Interpretation
Spectral signature
Geochemical signature
Geophysical signature
Reclassification

(ii) processing the available exploration datasets in order to obtain evidential maps

Database

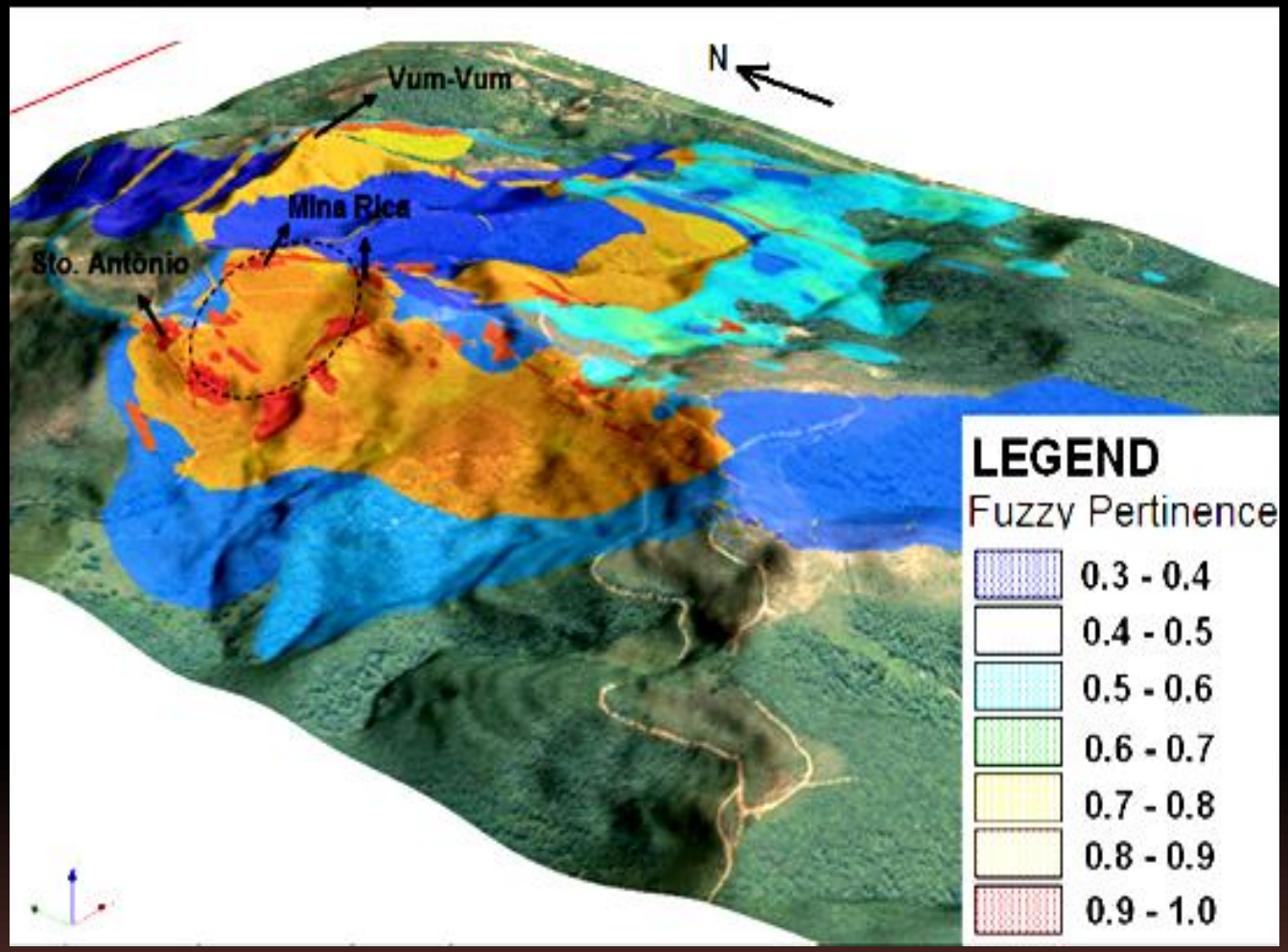
Geology | Rem. Sensing | Geophysics | Geochemistry

(i) conceptual modeling; identification of possible evidential maps; and formatting database in a GIS environment

Metallogenic Model

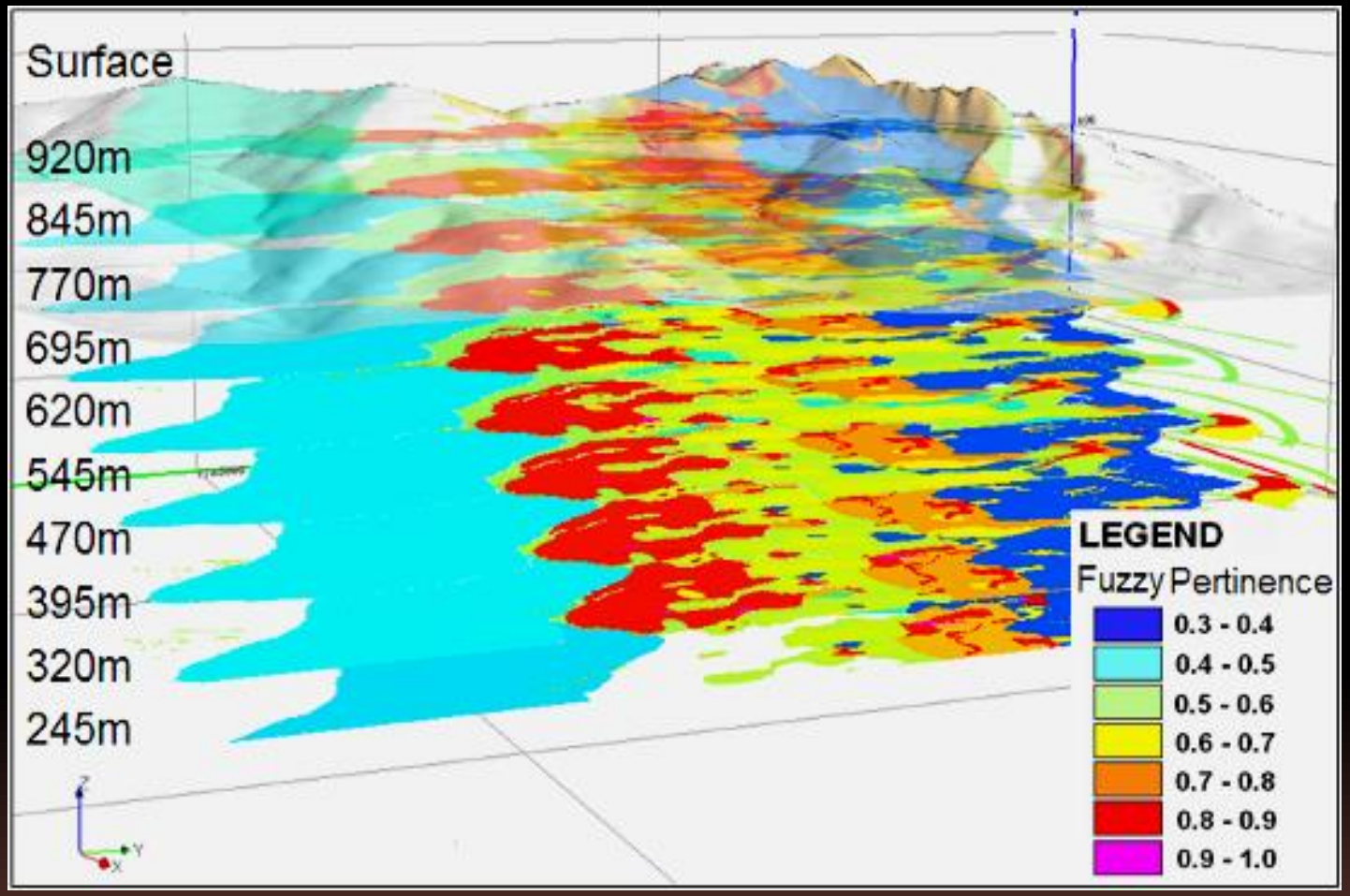
COSTA SILVA et al. (2012)

Gold deposit of Morro da Glória, Quadrilátero Ferrífero (MG)



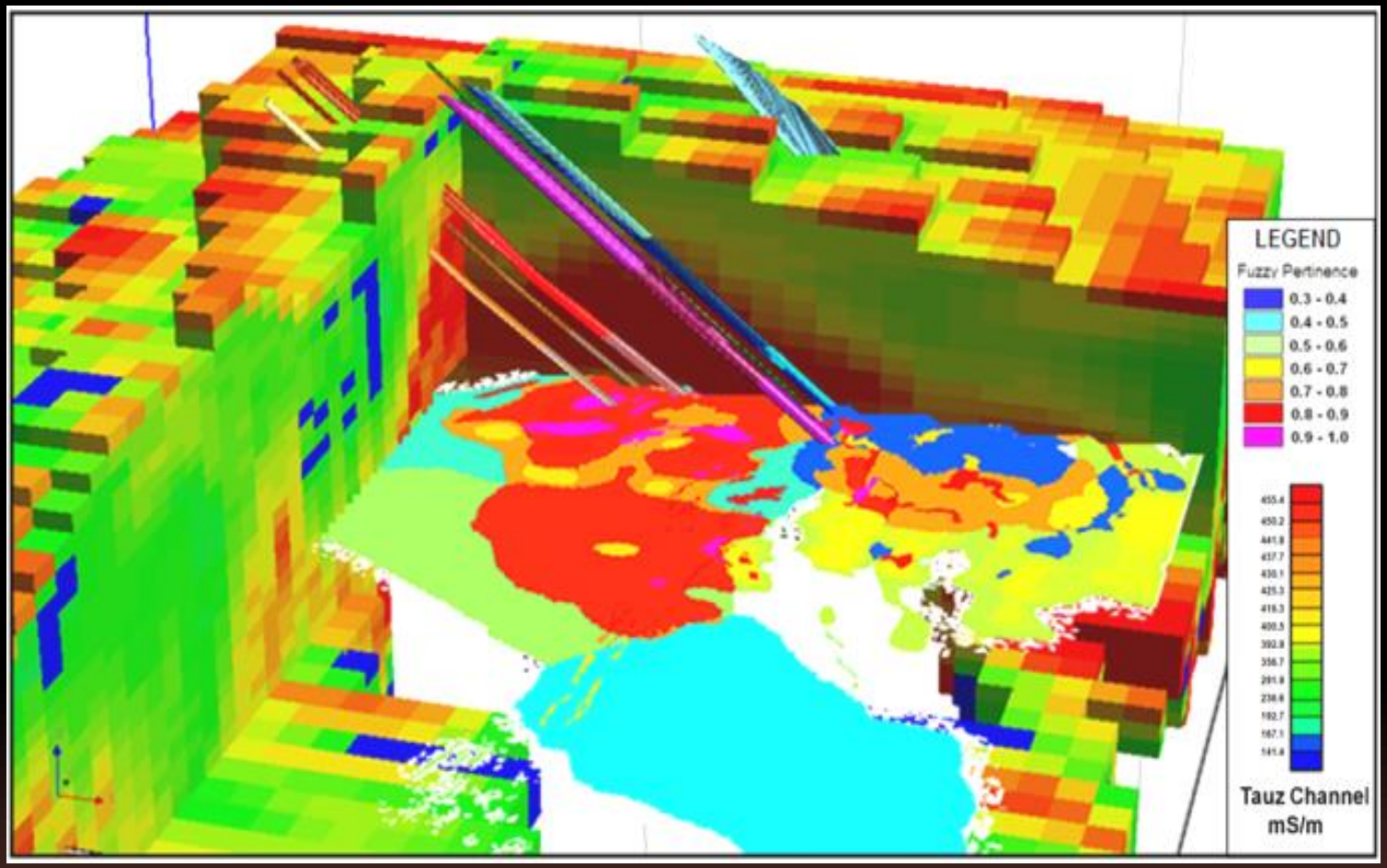
Fuzzy prospectivity model produced with evidential maps yielded from surface data. Red patches indicate higher potential areas. Source: Guimarães & Souza Filho (2011)

Gold deposit of Morro da Glória, Quadrilátero Ferrífero (MG)



Fuzzy prospectivity model (sliced by depth) produced with evidential maps yielded from **sub-surface** data. Red patches indicate higher potential areas. Source: Guimarães & Souza Filho (2011).

Gold deposit of Morro da Glória, Quadrilátero Ferrífero (MG)



Fuzzy prospectivity model (sliced by depth) produced with evidential maps yielded from sub-surface data. Red patches indicate higher potential areas. Source: Guimarães & Souza Filho (2011).

Current and Future Trends in Integration of Geological Datasets

Current trend for the generation of mineral prospectivity maps: descriptive models for deposits are replaced for models of mineral systems

Important innovations have taken place aimed at strengthening the relationship between processes and products based on prospectivity modeling in 3D and 4D

Significant advance should take place in the digital processing area aiming at the inversion of geophysical data and development of 3D voxel models or more advanced types

However, experiments with orbital geophysical data, such as those derived by gradiometry (electrostatic gravity gradiometer) from the satellite GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) show a promising future for the development of regional prospectivity models in greenfield areas. The use of such data can still be maximized from its integration with hyperspectral satellite data, covering the reflected and thermal spectrum, which should be launched between 2017-2022, such as the EnMap (Environmental Mapping and Analysis Program; DLR) and HyspIRI (Hyperspectral Infrared Image, NASA).

Mineral Exploration in Brazil
SOME CRITICAL ASPECTS

Low confidence on the regional and local geological maps;

Despite new concepts and fundamental knowledge we need better understanding of key features that are critical in exploration targeting and discovery;

No record, of a list of deposit attributes, conceptual models or a complete metallogenetic exploration model guides;

The empiric models have been used by Brazilian explorationists as a strategic advantage, though serendipity has played an important role as an innovation driver;

The modern concept of Mineral Systems is loosely used in mineral exploration in Brazil;

The discoveries were due to real techniques already tested;

The lack of 3D data on a regional scale is another challenge to be overcome in the future.

CHALLENGES IN MINERAL EXPLORATION

The present exploration challenge: how to benefit from the huge amount of data gathered during exploration campaign in Greenfield and Brownfield environments?

The growing use of geotechnologies will allow the total integration of geologiacal, geophysical , geochemical data in 3D-4D, and comprehension of geological processes at all scales;

Regional metallogenetic analyses based on the mineralization expression favors 3D-4D integration of geophysical, geochemical, remote sensing, and field mapping results;

New deep exploration and techniques are required to meet the future needs of industry;

Innovation & success in mineral exploration in Brazil: continues to be loosely documented: the wealth of data are kept in the hands of mining companies and government agencies;

Global tendency

Ore deposit modeling: descriptive deposit models replaced for Mineral Systems concepts;

Requirements: multidisciplinary investigation (eg. geodynamic, lithospheric arquitecture, translithospheric structures, distal footprints of giant deposits).

Comprehension of mineralization processes at all scales and transposition to exploration models;

Generation of mineral prospectivity maps strengthening the relationship between processes and products based on integration model in 3D and 4D;

How to overcome?

The discovery of resources and new ore deposits in our known metallogenetic provinces demand robust geological and exploratory models scientifically supported.

Collaborative network among the exploration industry, university research groups, the government geosciences, and corporate research centers (key research themes);

Formation of creative exploration geologist, geophysicist and geochemist, generation of innovative ideas and hypotheses of ore genesis necessary for new discoveries, and support for corporate or individual decision making;

The huge amount of data, and development of analysis tools do not substitute for the basic geology and geological processes, and creativity of exploration geologists.

Thank you!