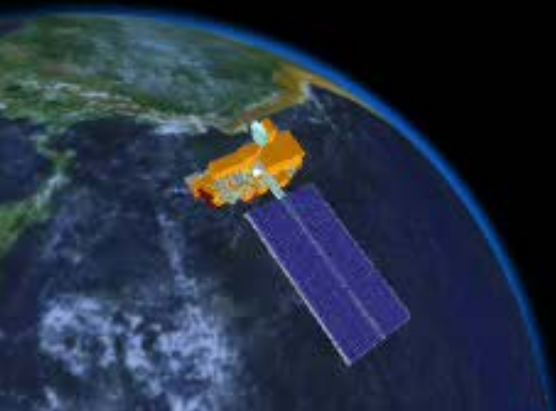
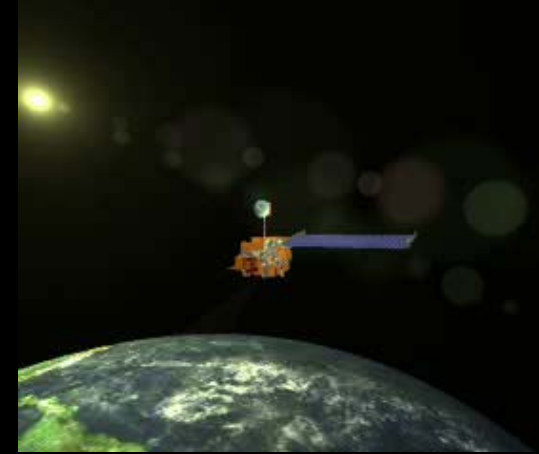
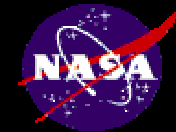




*From Gamma-Ray, through
Visible, Infrared to
Microwave Wavelengths:
Applications of the Full EM
Spectrum in Mineral and
Hydrocarbon Exploration*

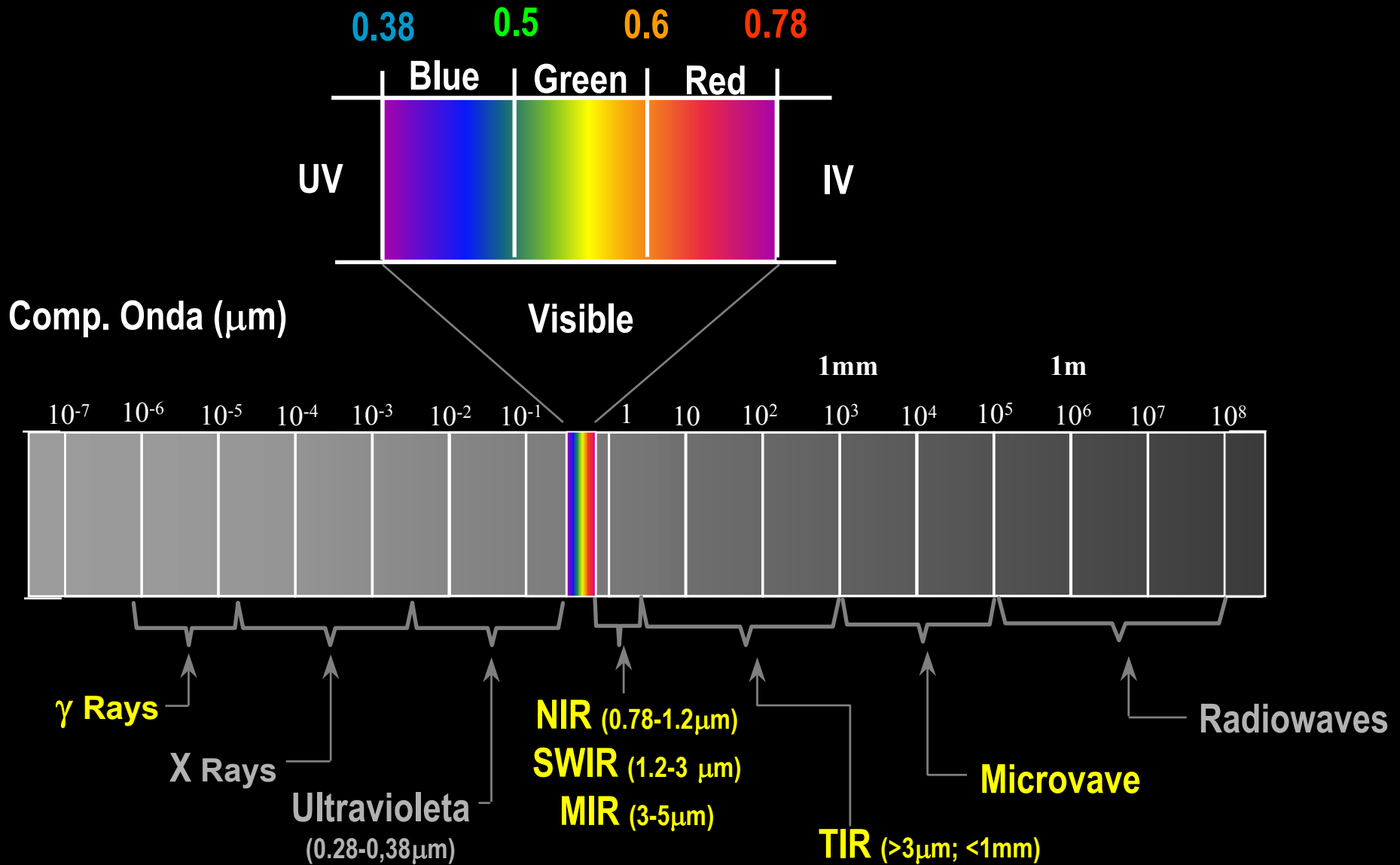


Carlos Roberto de Souza Filho
Grupo de Pesquisa em Geotecnologias
Dept. de Geologia e Recursos Naturais
Instituto de Geociências
UNICAMP



UNICAMP

O Espectro Eletromagnético



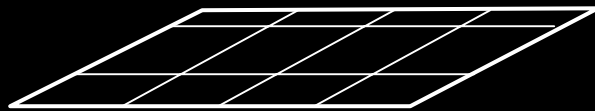
Introdução

- ❖ Dados de **Sensoriamento Remoto 'ótico' orbital (VIS-NIR-SWIR-TIR)** aplicáveis a problemas geológicos, particularmente na exploração mineral e petrolífera, são praticamente limitados atualmente as **imagens multiespectrais** dos sensores **TM-ETM+/ Landsat e ASTER/Terra**.
- ❖ Os **métodos de processamento** desses dados, visando o realce de **informações direta** ou **indiretamente** relacionadas a **depósitos metálicos** e **reservatórios de petróleo**, podem ser divididos em: (i) **convencionais** (razão de bandas, índices espectrais, APCs, etc), (ii) **hiperspectrais adaptados** a dados multiespectrais, (iii) **redes neurais (classificação espectro-espacial)**.
- ❖ Os **resultados** obtidos com a aplicação dos vários métodos convencionais e mais sofisticados mostram **grande similaridade**, diferindo principalmente quanto a **medida do "erro" associada** ao mapeamento de feições de interesse.

EXPERIÊNCIA ⇒ sucesso de uma aplicação de SR em exploração mineral ou petrolífera ⇒ **MODELO DE DETECÇÃO**

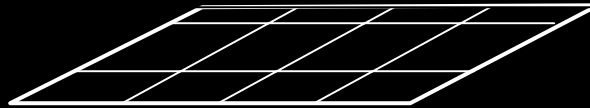
MODELO DE DETECÇÃO → **DESCRITIVO !**

Fenômenos **OBSERVÁVEIS**



“Filtro 1” → **Condicionantes Ambientais**
- clima, vegetação, solo...

Fenômenos **DETECTÁVEIS**



→ **Espectrorradiometria**

“Filtro 2” → **Dados**
- disponibilidade, resolução,
escala, custos...

Seleção de Dados

Processamento de Imagens

→ **Modelagem Espectral**

Análise e Interpretação

Imagens Temáticas

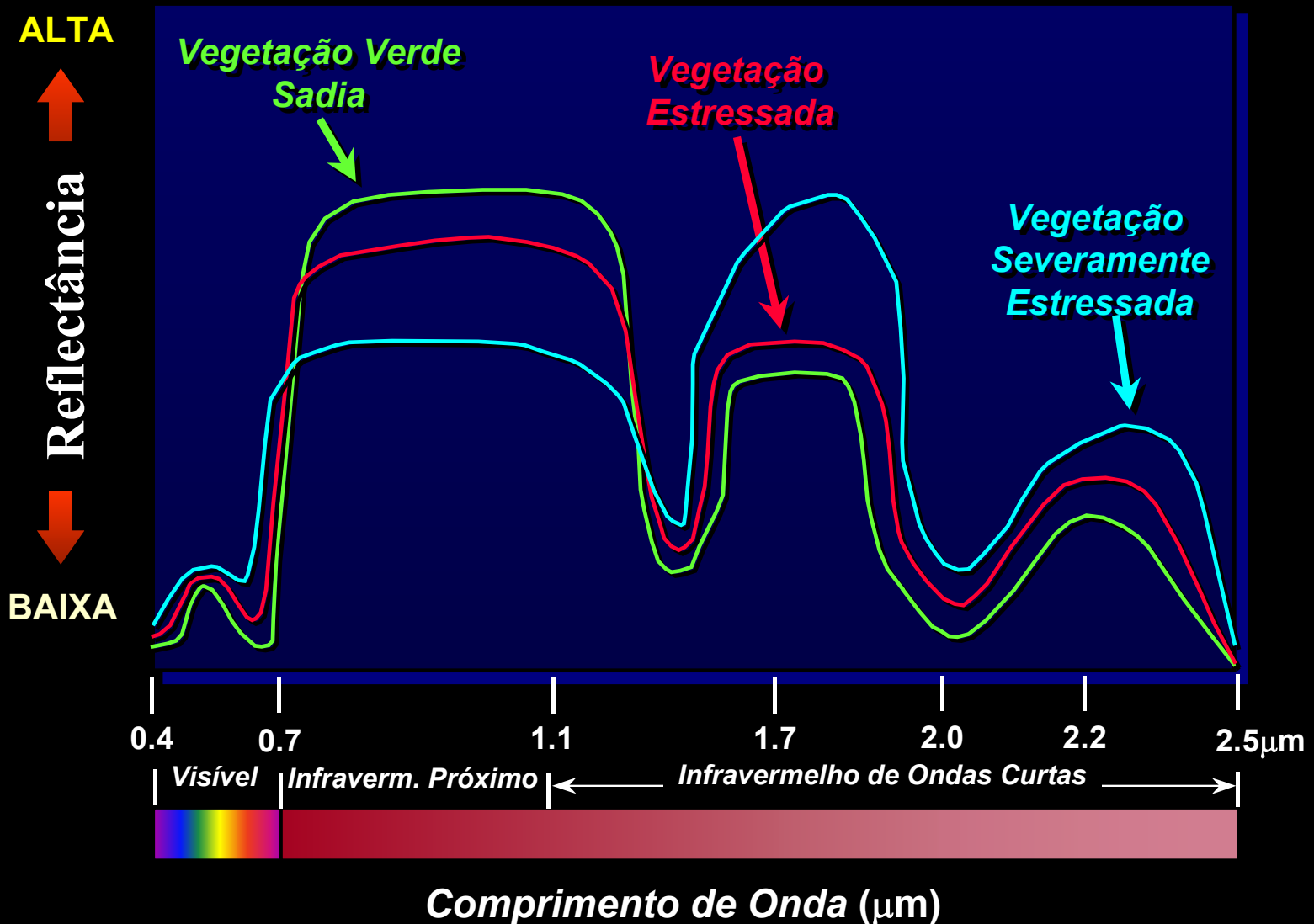
Integração & Validação

OBJETIVO



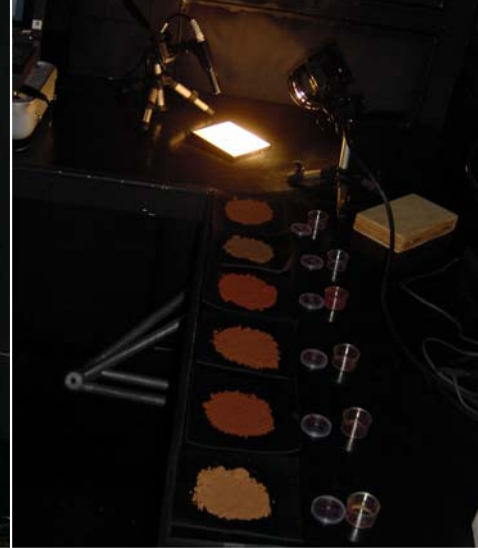
**ALVOS
EXPLORATÓRIOS**

Fenômenos **DETECTÁVEIS** - teóricos



Curvas de Reflectância Espectral de Vegetação Sadia e Estressada

Fenômenos **DETECTÁVEIS** experimentais



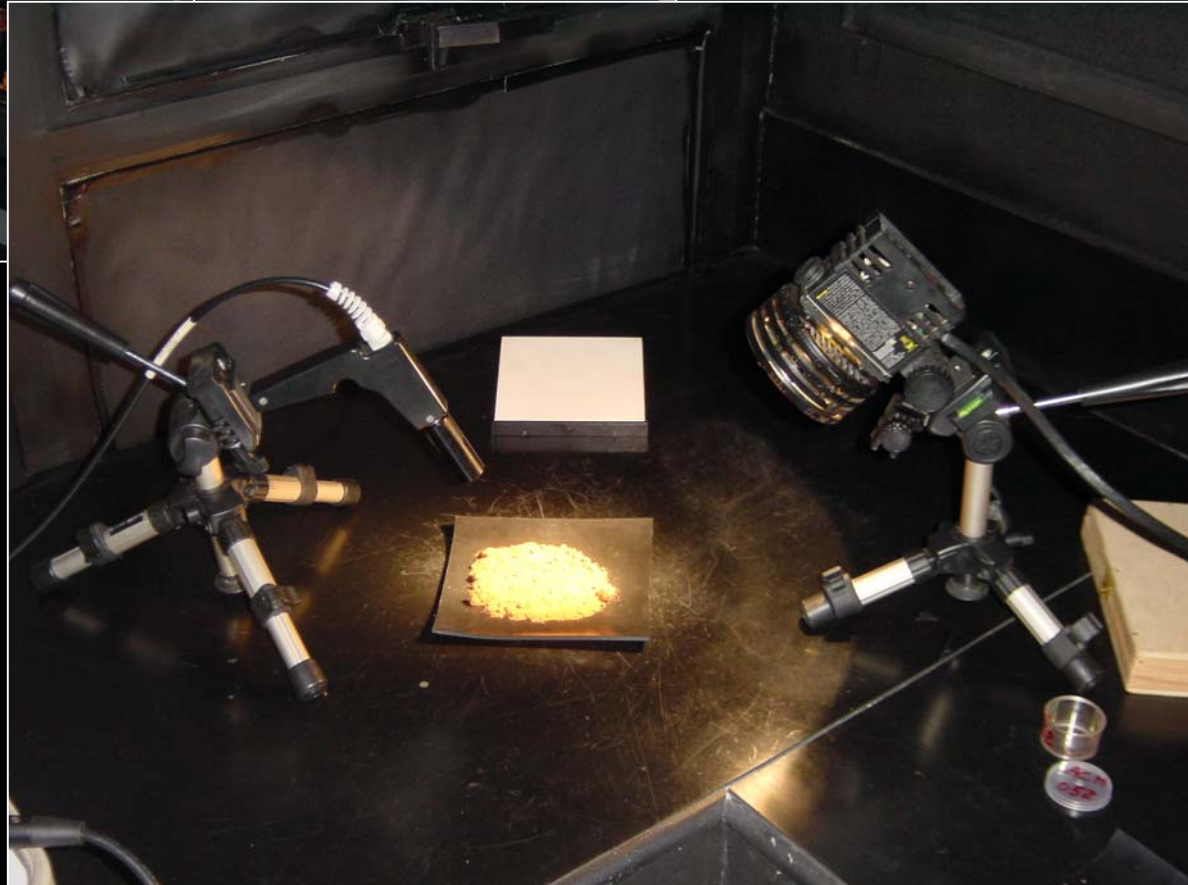
*Laboratório de
Espectroscopia de
Reflectância (LER)
IG-UNICAMP*

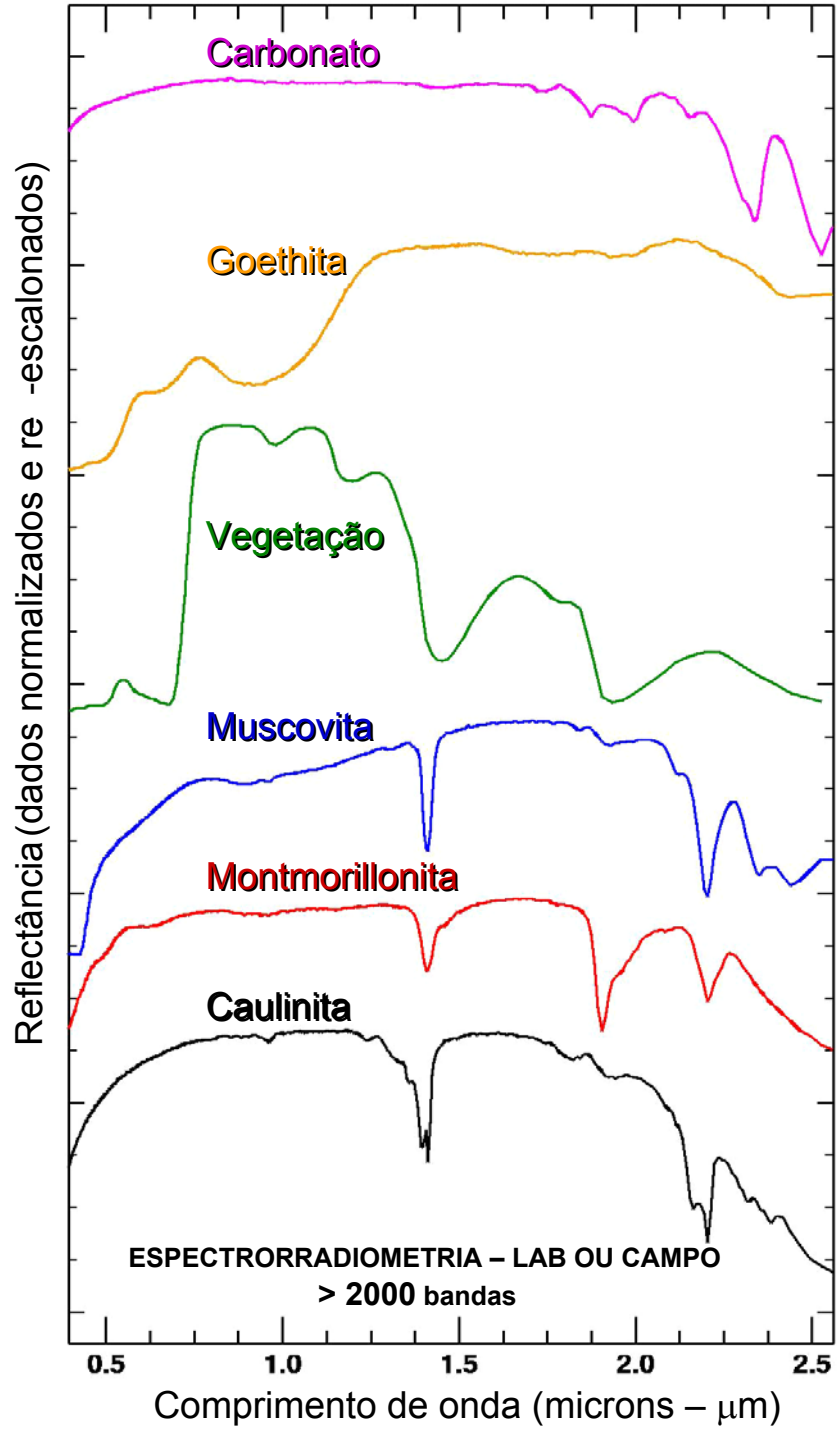
Espectrorradiometria

**ASSINATURA ESPECTRAL DOS
ALVOS**

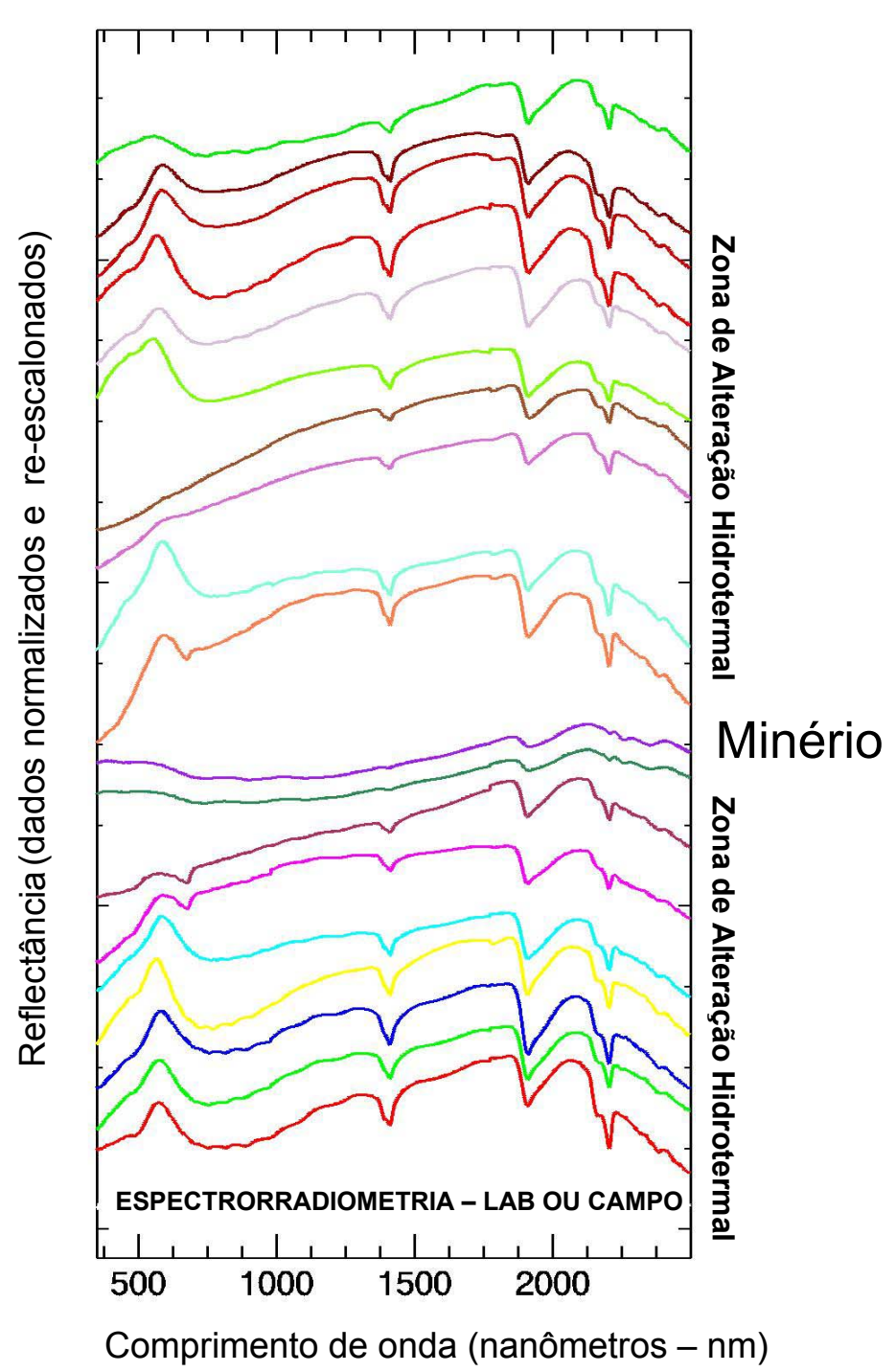


**ANALISE QUALITATIVA E
QUANTITATIVA**



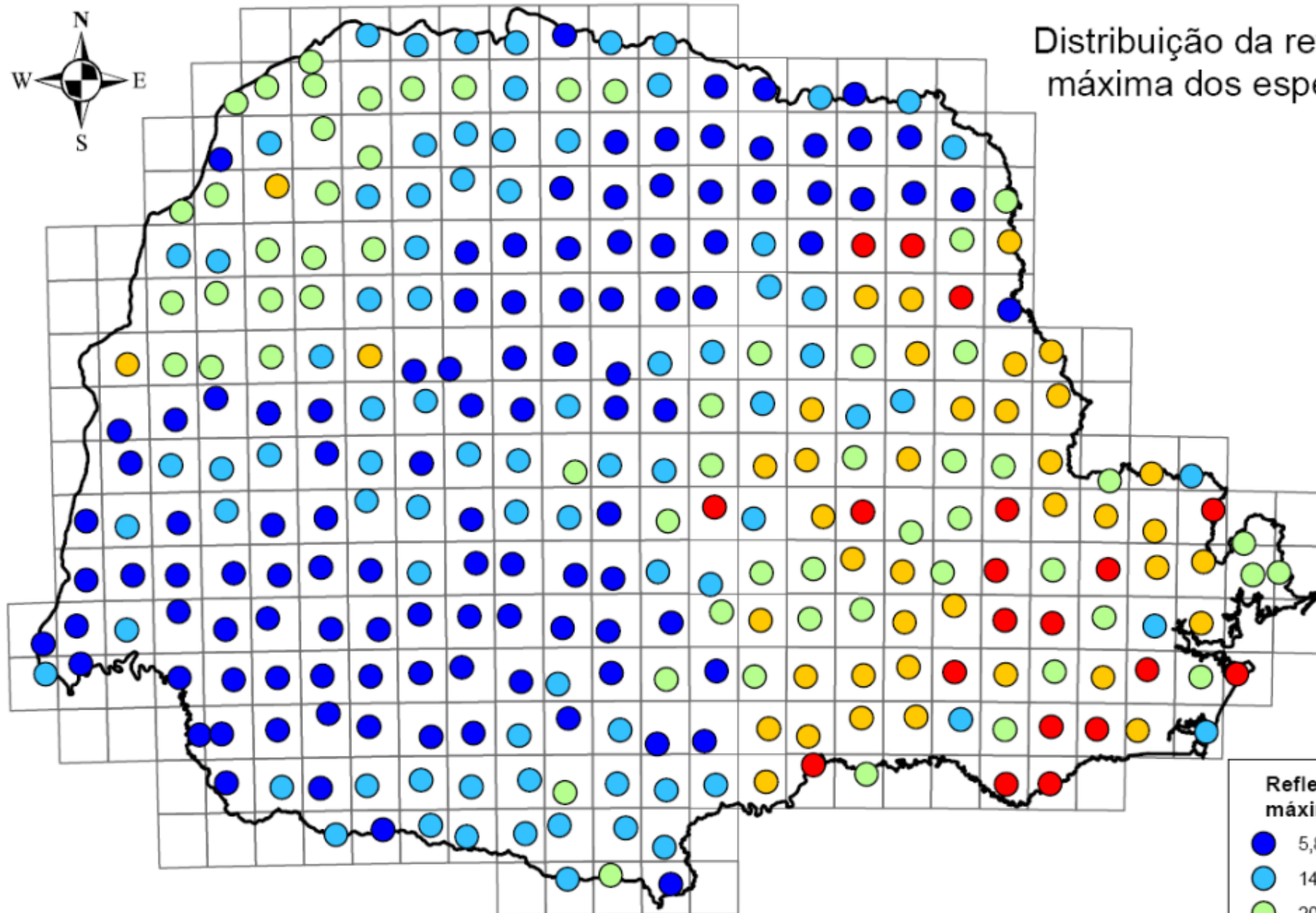


**FENÔMENOS DETECTÁVEIS
(materiais específicos ou assinaturas de misturas)**





Distribuição da reflexão máxima dos espectros

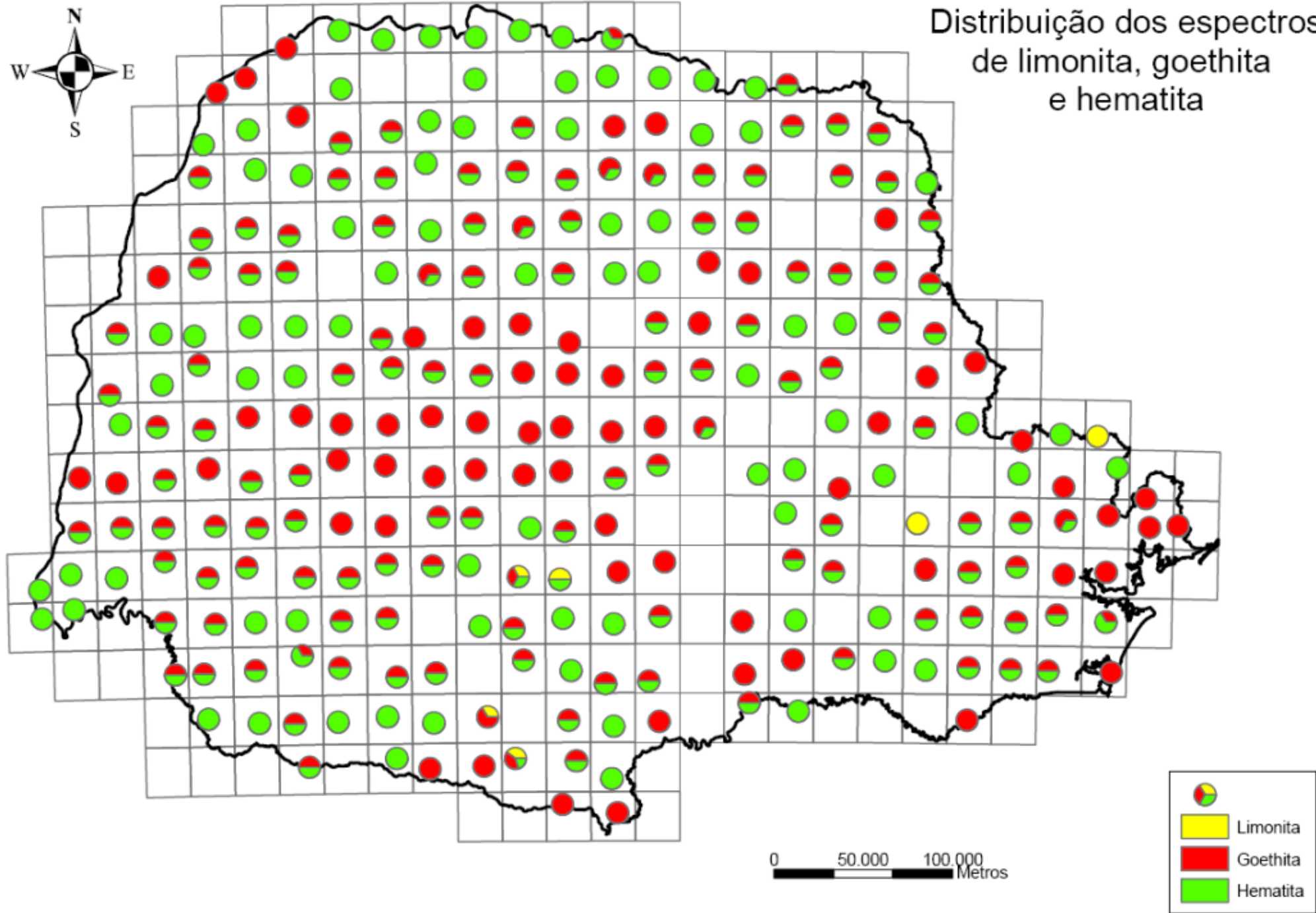


0 50.000 100.000 Metros

Reflexão máxima (%)

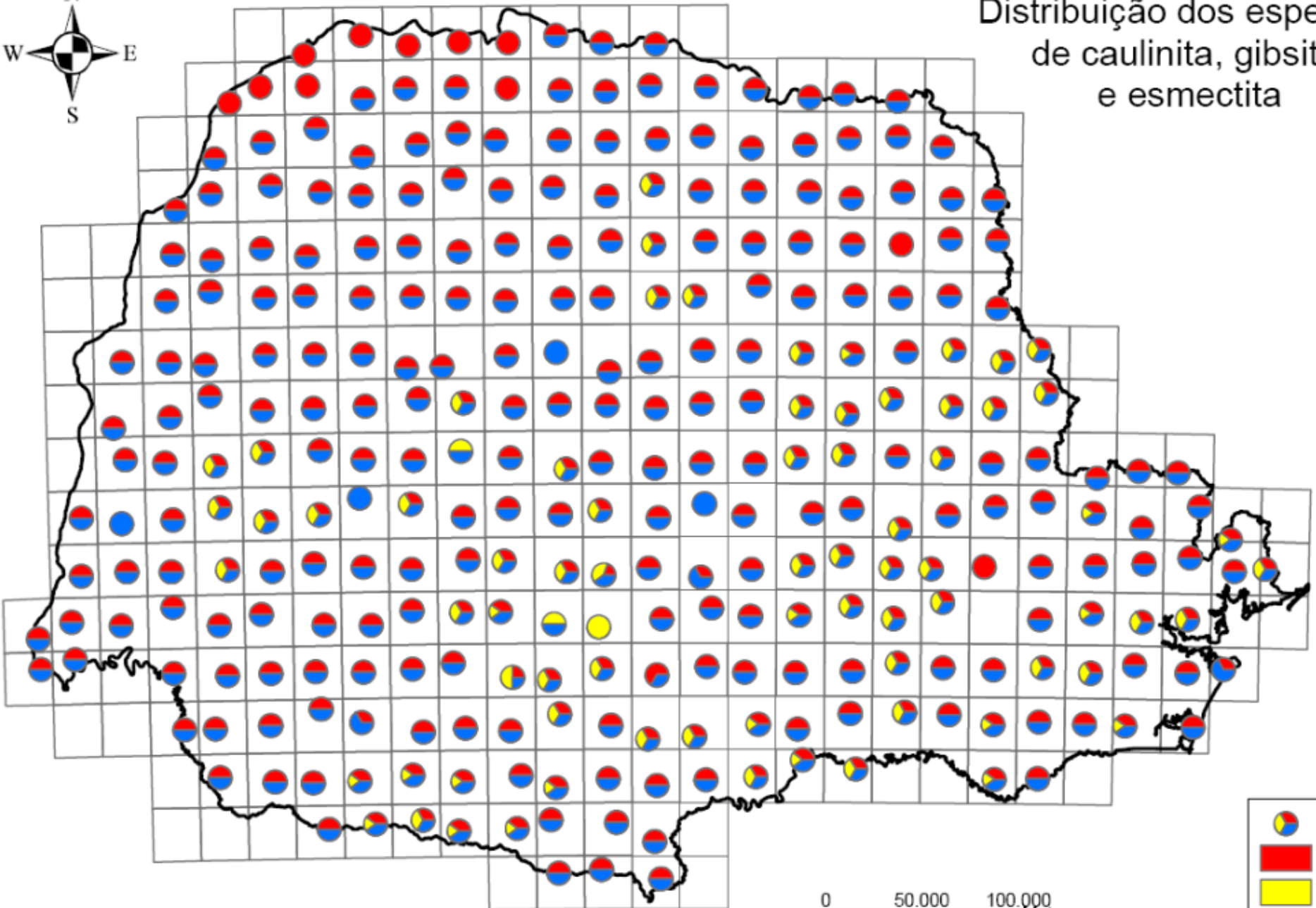
- 5,87 - 14,18
- 14,18 - 20,87
- 20,87 - 29,55
- 29,55 - 44,49
- 44,49 - 66,57

Distribuição dos espectros de limonita, goethita e hematita

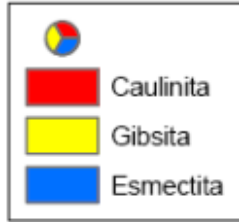


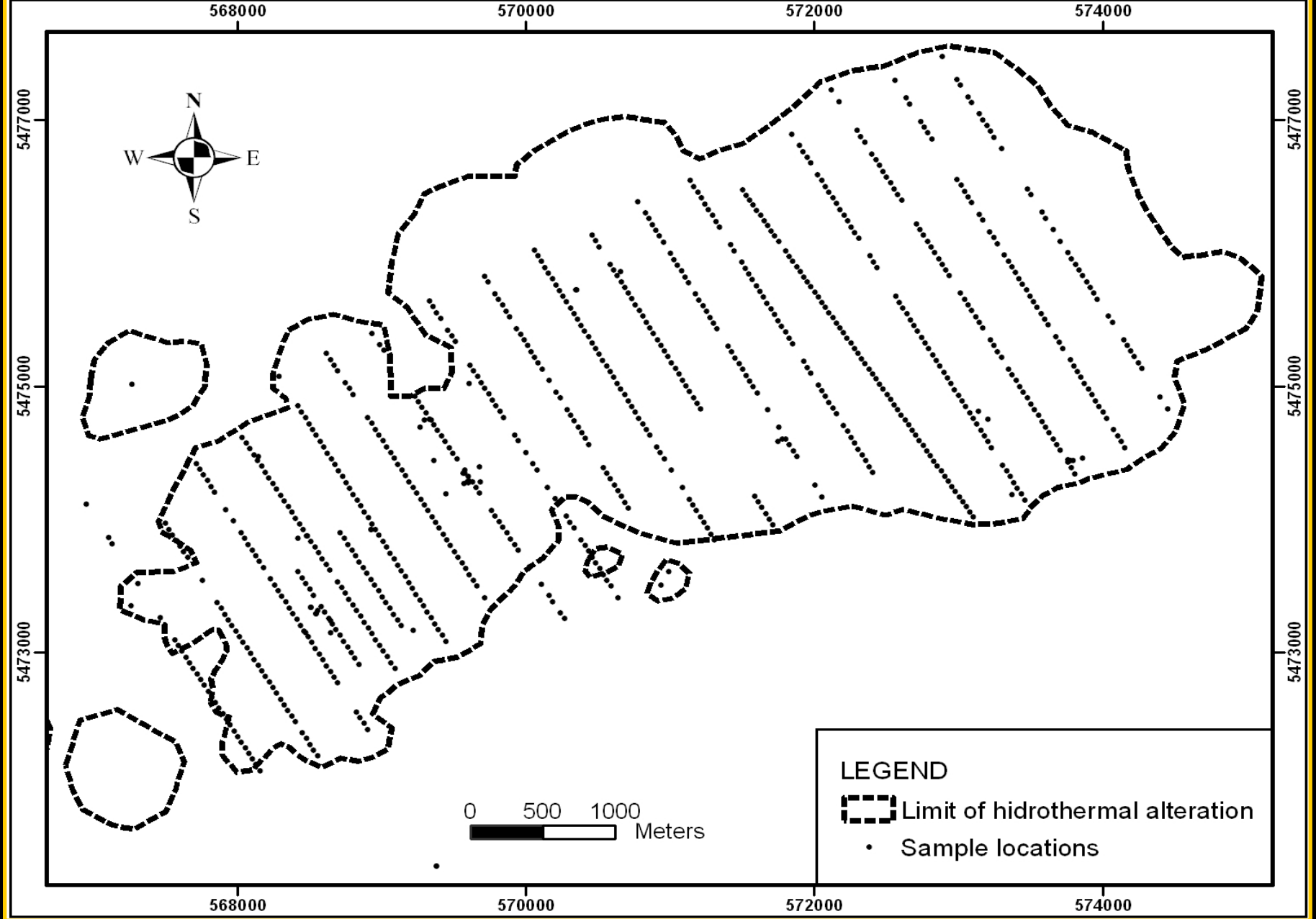


Distribuição dos espectros de caulinita, gibsita e esmectita

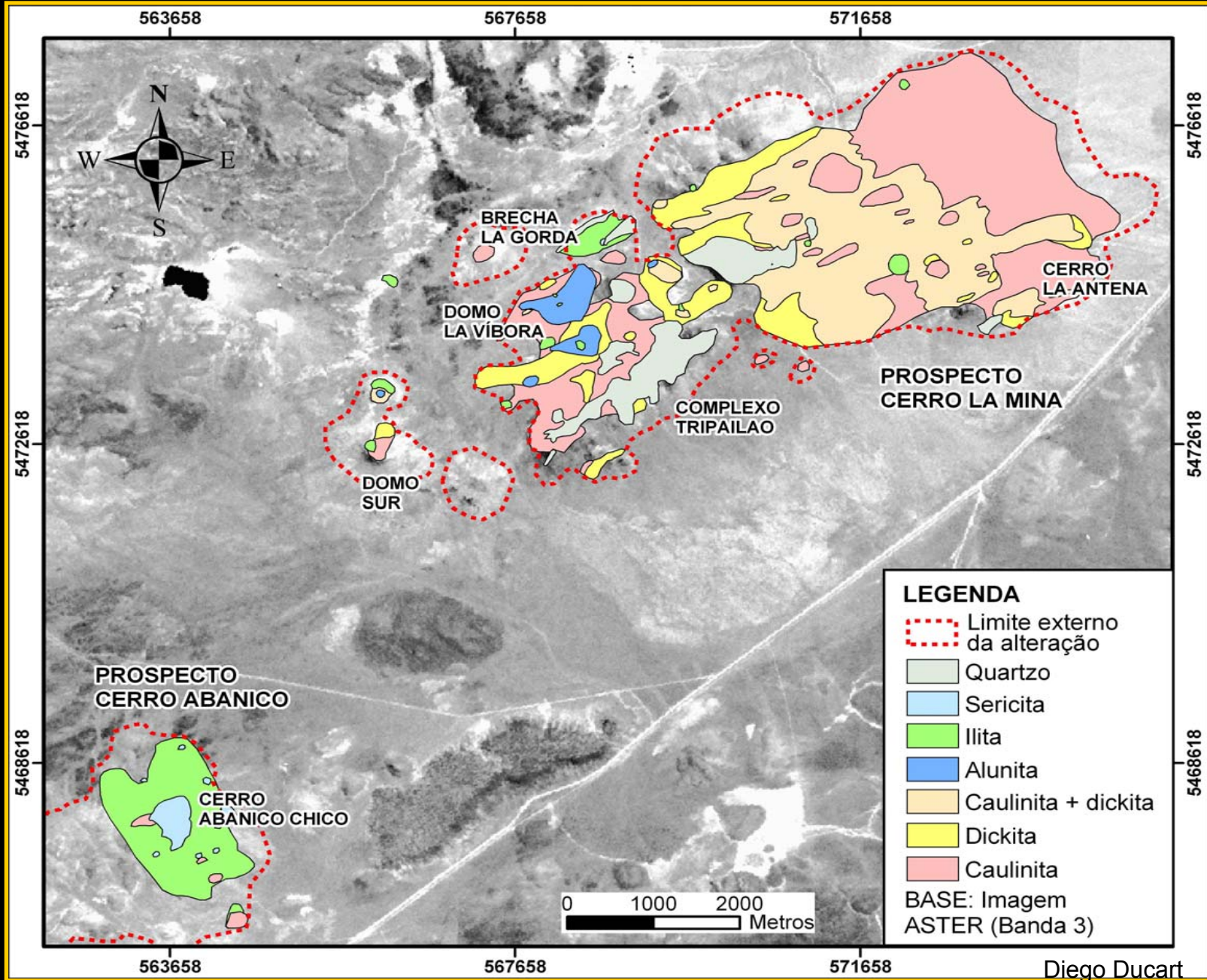


0 50.000 100.000 Metros





Malha de amostras medidas no campo por espectrorradiometria em Los Menucos (Patagonia – Argentina)



Diego Ducart

MAPA DE ALTERAÇÃO HIDROTHERMAL BASEADO EM MEDIDAS ESPECTRORRADIOMÉTRICAS E INTERPRETAÇÃO ESPECTRO-MINERALÓGICA (Los Menucos)

- MODELOS DE EXPLORAÇÃO **MINERAL** EM TERRENOS **SEM COBERTURA VEGETAL**
 - **Detecção de minerais de alteração** hidrotermal expostos em superfície é direta e minerais particulares, como “argilas”, funcionam como **vetores para localização de corpos de minério**.

- MODELOS DE EXPLORAÇÃO **MINERAL** EM TERRENOS **COM COBERTURA VEGETAL**



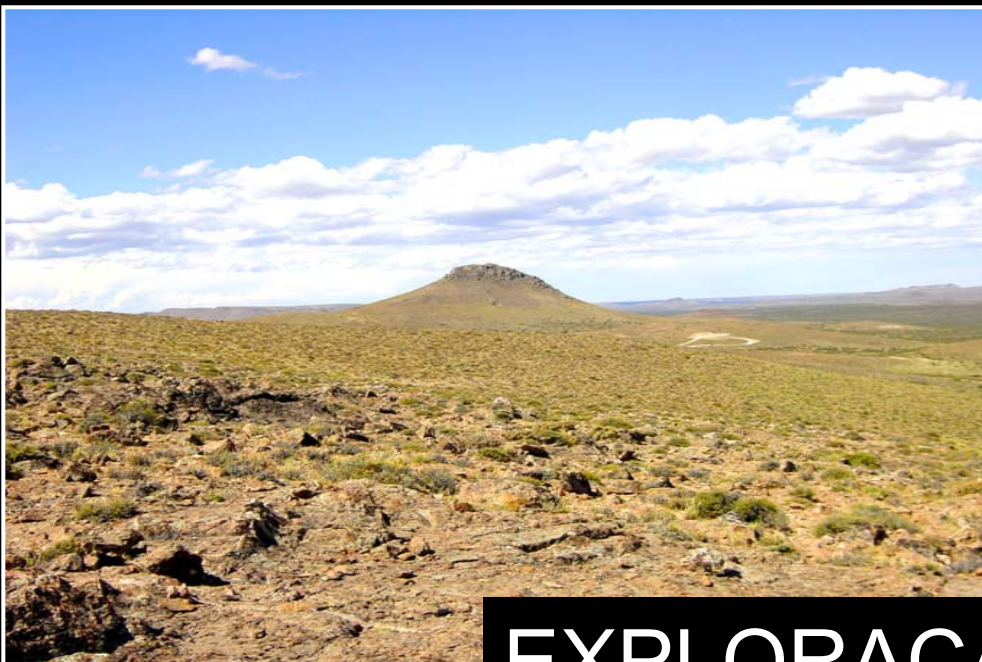
MISSÃO IMPOSSÍVEL ?

- Não !
- Zonas de alteração hidrotermal \Rightarrow solos \Rightarrow nichos de **vegetação DISSIMILAR** em florestas tropicais \Rightarrow aproximações **GEOBOTÂNICAS**

Patagonia (Au)

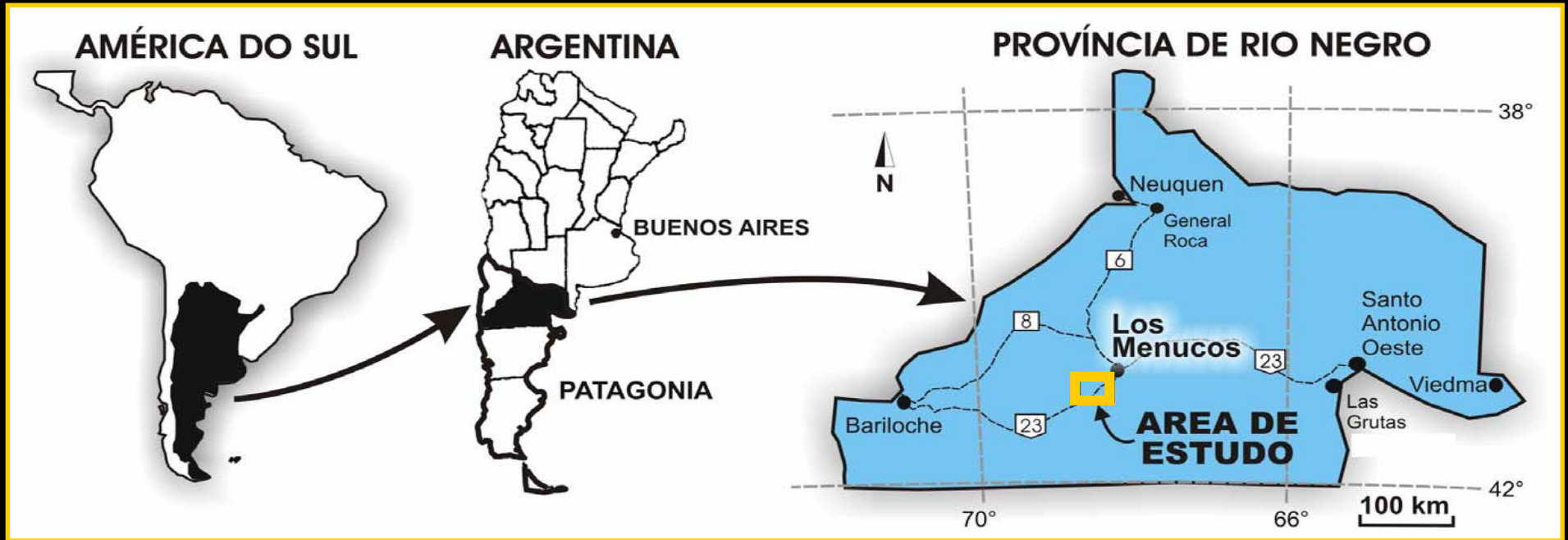


Tapajós (Au)



EXPLORAÇÃO MINERAL

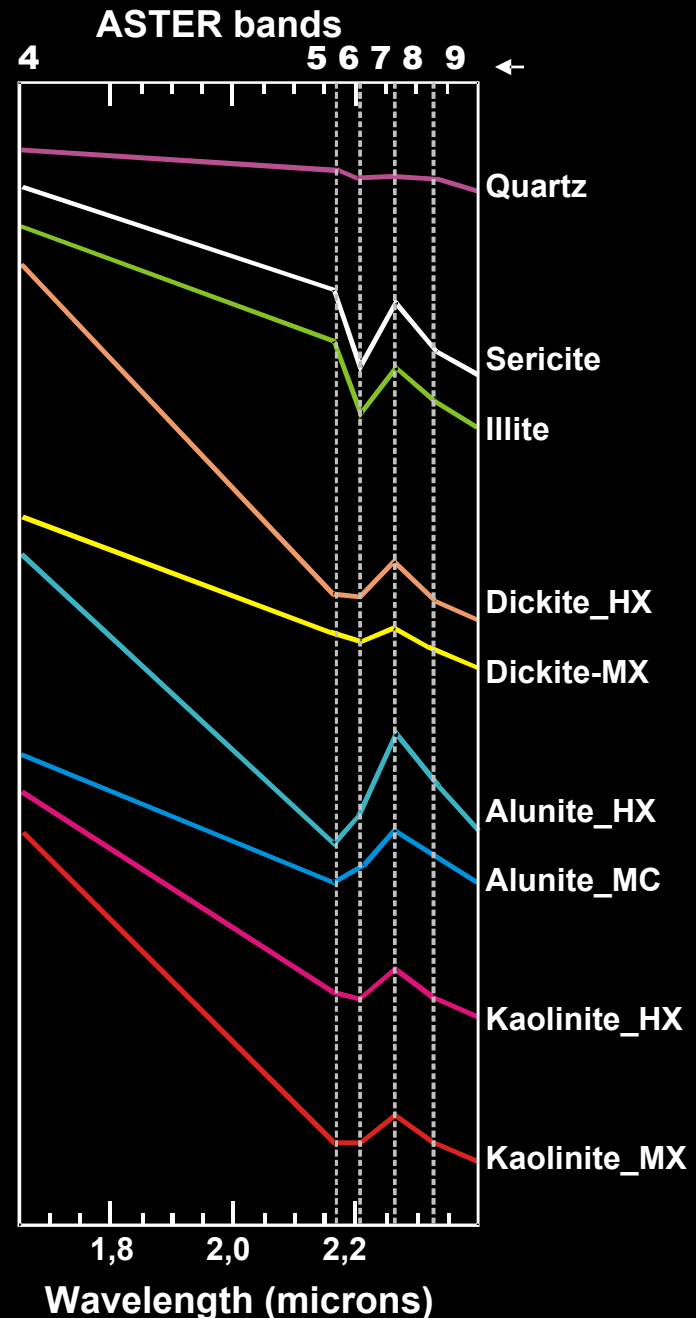
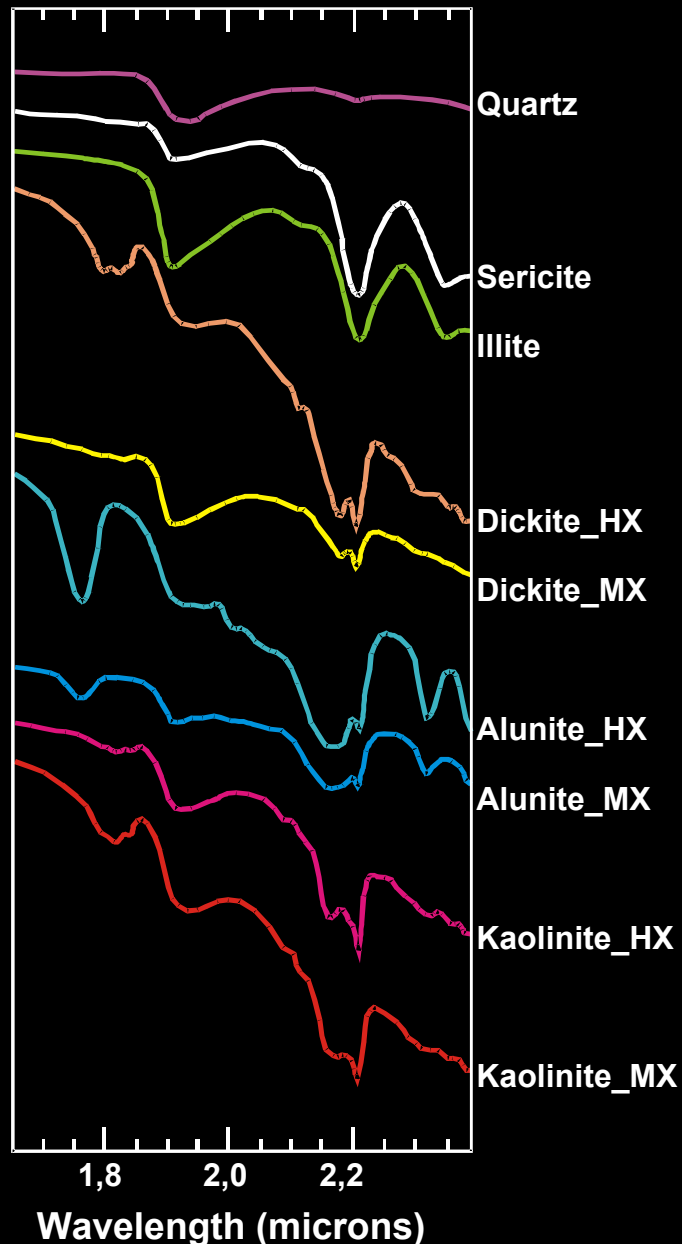
Distrito de Los Menucos, Rio Negro



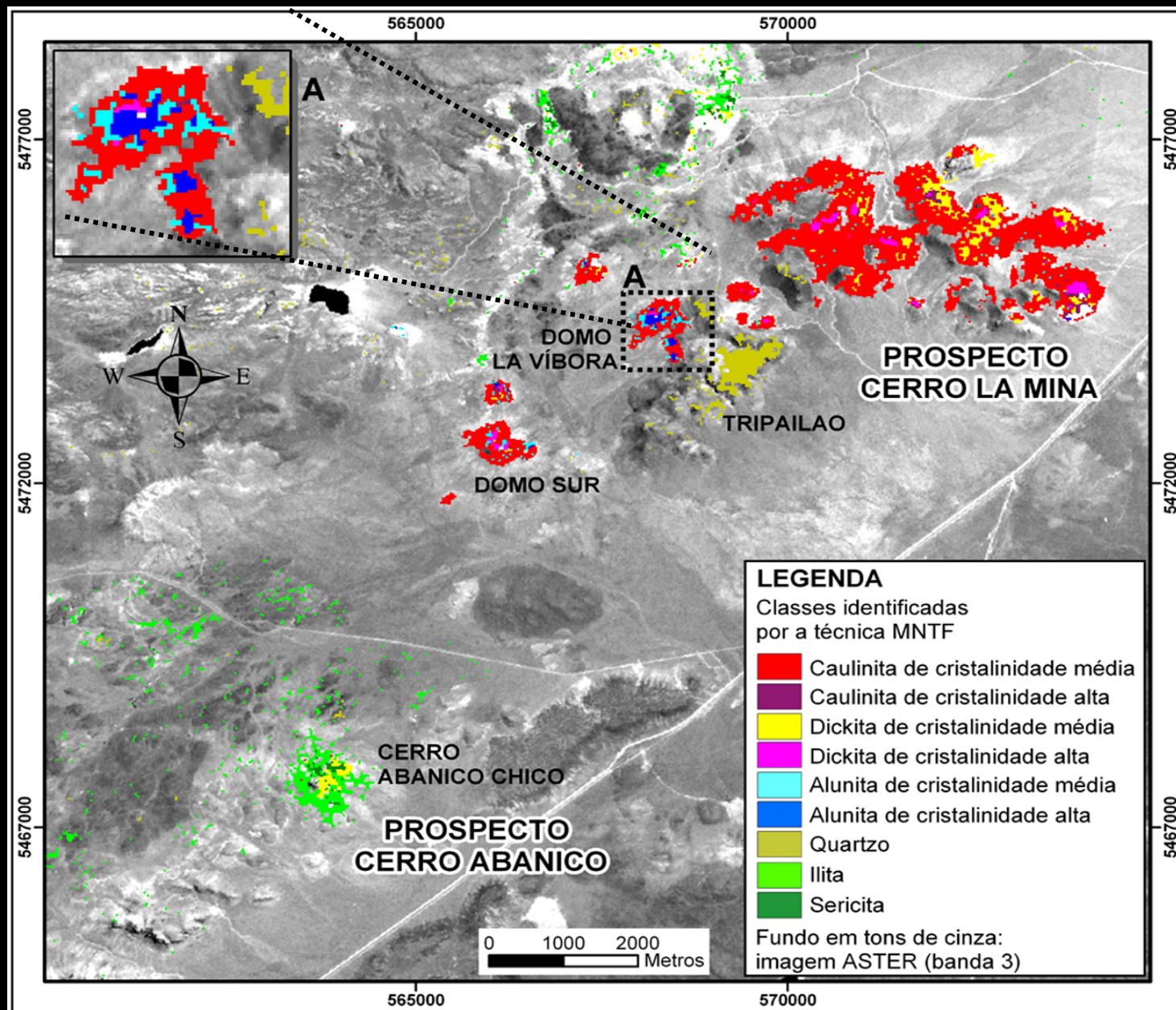
Mapa de Alteração Hidrotermal Gerado por Técnicas de Processamento Convencionais (PCs) Aplicadas aos dados TM/Landsat-5



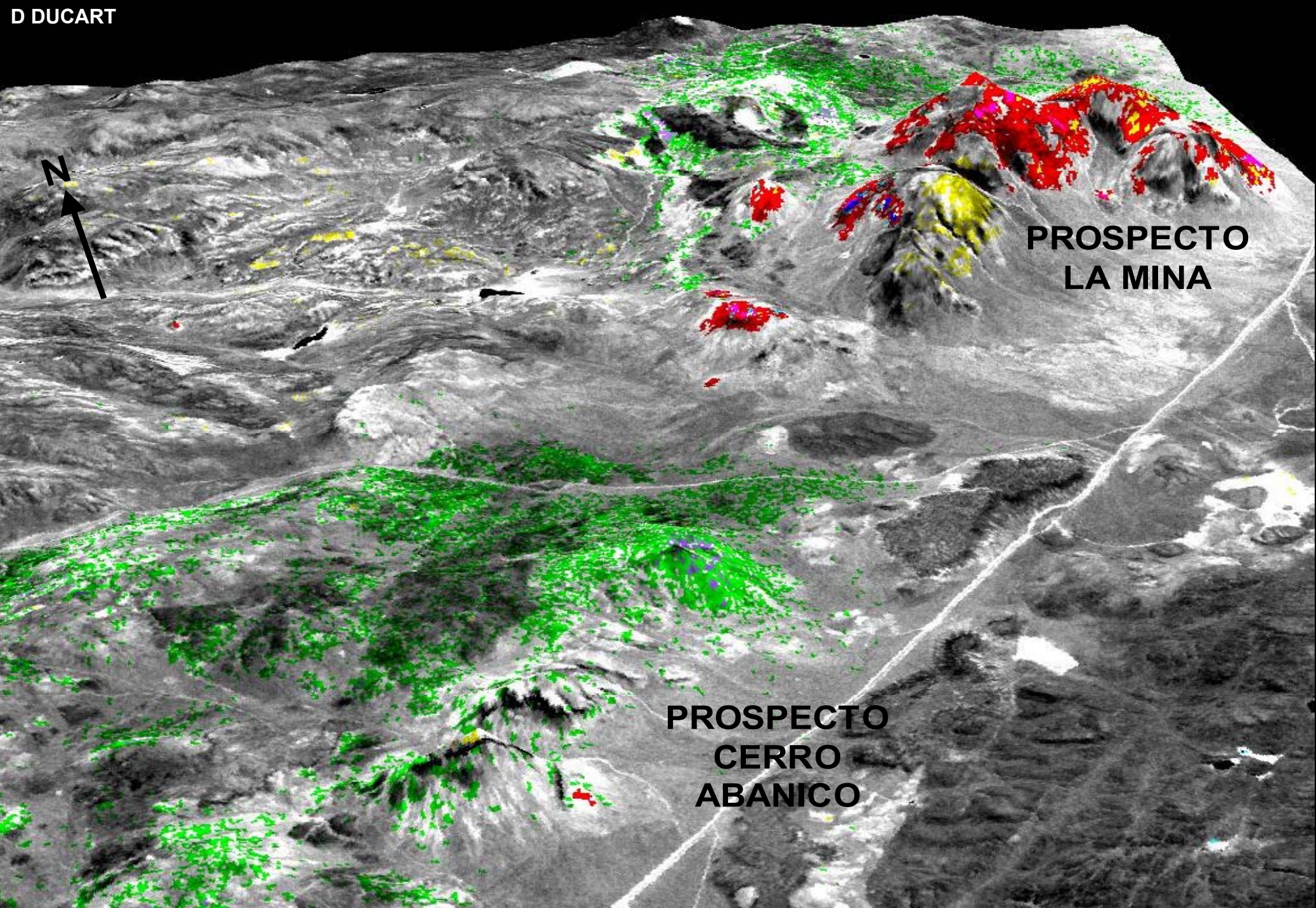
Biblioteca Espectral



Mapa de Alteração Hidrotermal Gerado por Técnicas de Processamento Hiperespectral Aplicadas aos dados ASTER



D DUCART

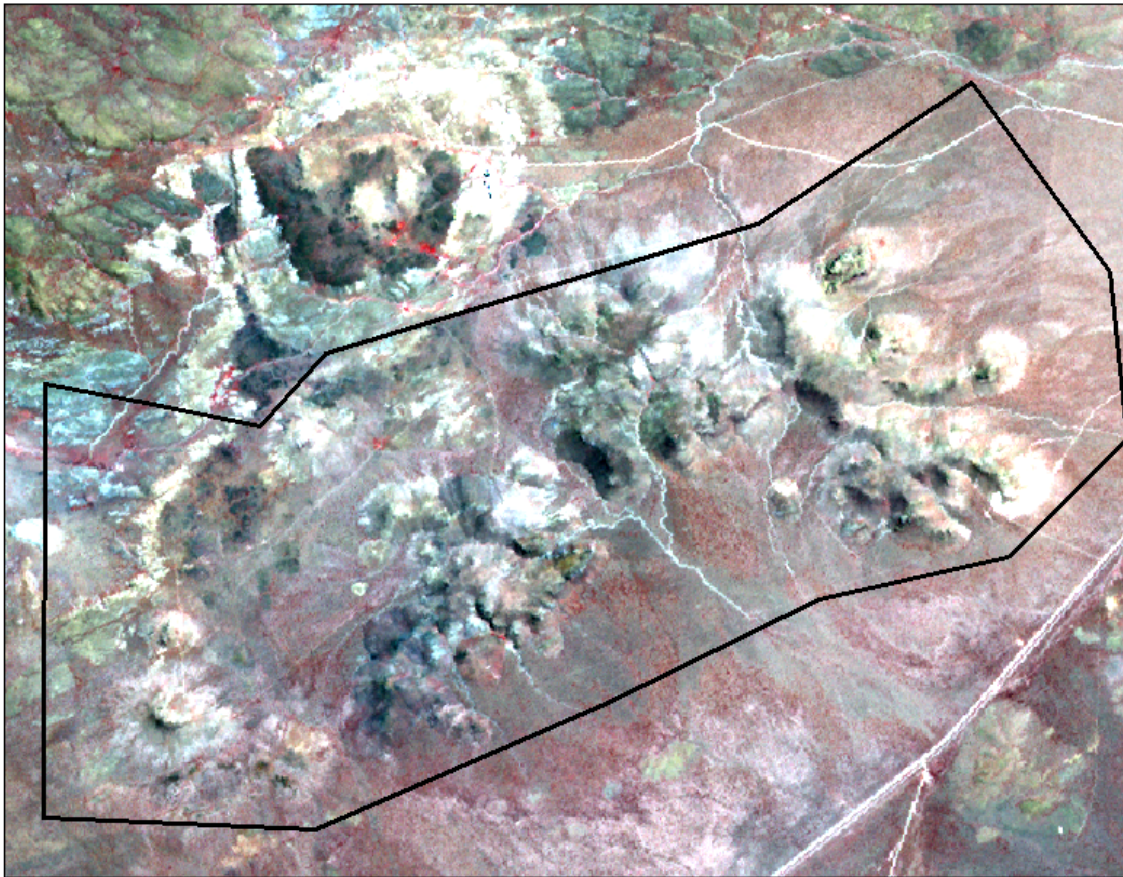


**PROSPECTO
LA MINA**

**PROSPECTO
CERRO
ABANICO**

Mapa de Alteração Hidrotermal Gerado por Técnicas de Redes Neurais Aplicadas aos dados ASTER

ASTER Color Infrared
Bands 321 (RGB)

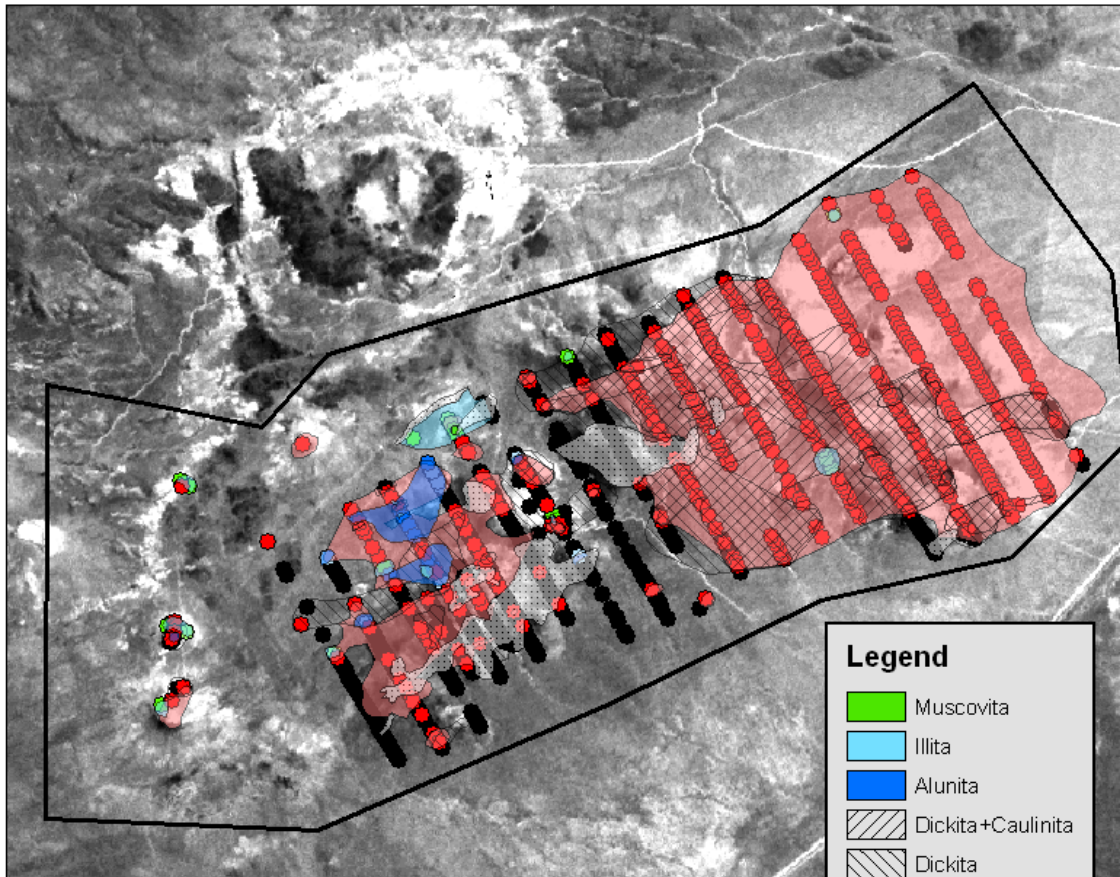


0 0.5 1 2 3 4 Kilometers

Aster Band 3 Image
Los Menucos Area
SDMUC11 060329

Mapa de Alteração Hidrotermal Gerado por Técnicas de Redes Neurais Aplicadas aos dados ASTER

ASTER Color Infrared Bands 321 (RGB)



0 0.5 1 2 3 4 Kilometers

Aster Band 3 Image
Los Menucos Area
SDMUC11 060329

Legend

- Muscovita
- Illita
- Alunita
- Dickita+Caulinita
- Dickita
- Caulinita

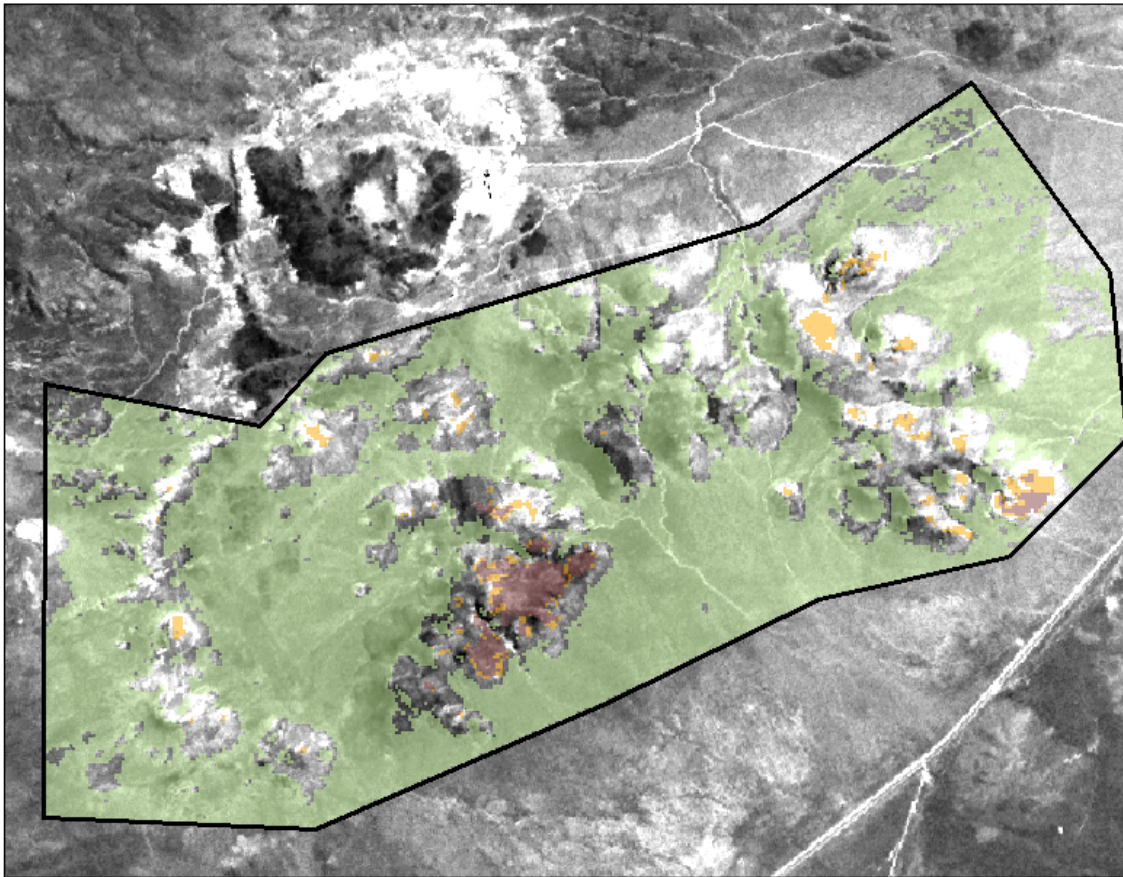
PIMA Groups

KAOL, ALU, IM

- Kaolinite
- Alunite
- KA
- IM
- IM
- None
- KIM

Mapa de Alteração Hidrotermal Gerado por Técnicas de Redes Neurais Aplicadas aos dados ASTER

Bands 321 (RGB)







0 0.5 1 2 3 4 Kilometers

Aster Band 3 Image
Los Menucos Area
SDMUC11 060329

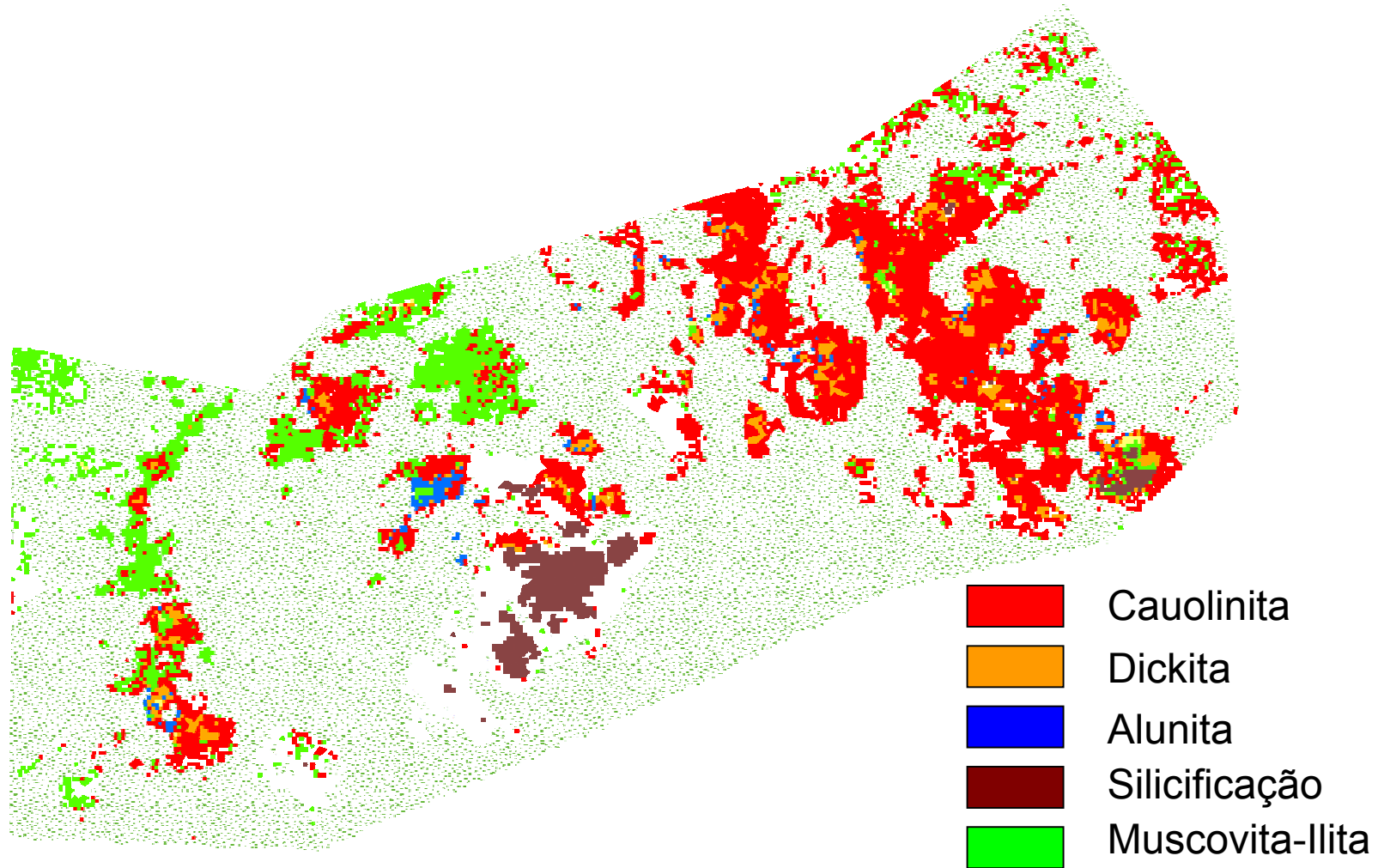
Legend

sdmuc11 Fuzzy 4 Cluster
sdmuc11_nnrsltc.FzzyClstr

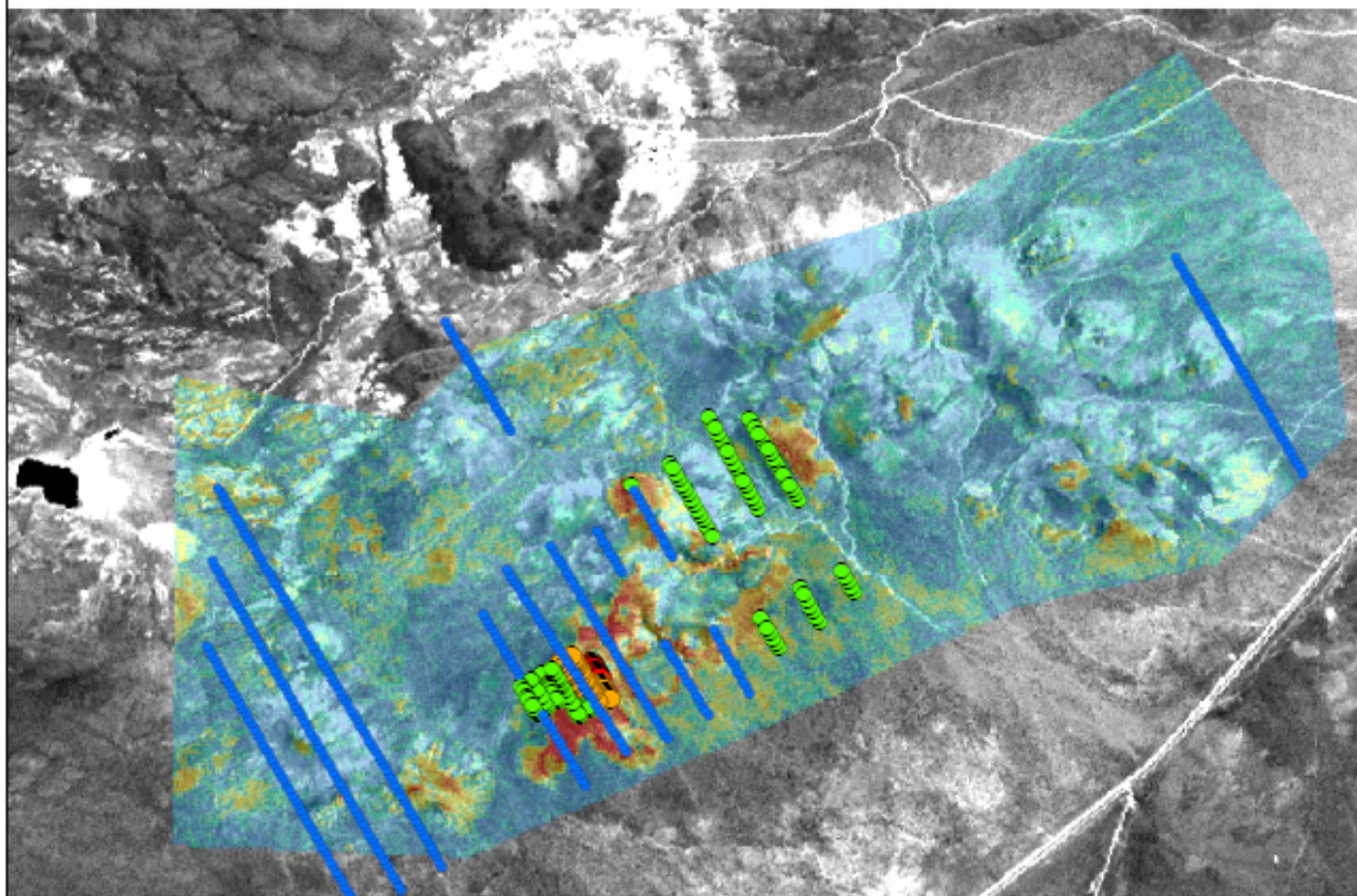
-  Kaolinite + Illite_Muscovite
-  Dickite + Kaolinite
-  Vegetation
-  Quartz

Four Fuzzy Neural
Network Clusters
Using Bands 1-9

Mapa de Alteração Hidrotermal Gerado por Técnicas de Redes Neurais Aplicadas aos dados ASTER



5 Kilometers



Legend

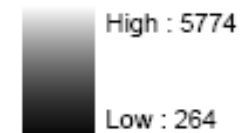
Lag_Au
AU

- 5 - 27
- 28 - 75
- 76 - 174
- 175 - 340

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9

ASTER Band1

Value



PNNetwork – Ouro

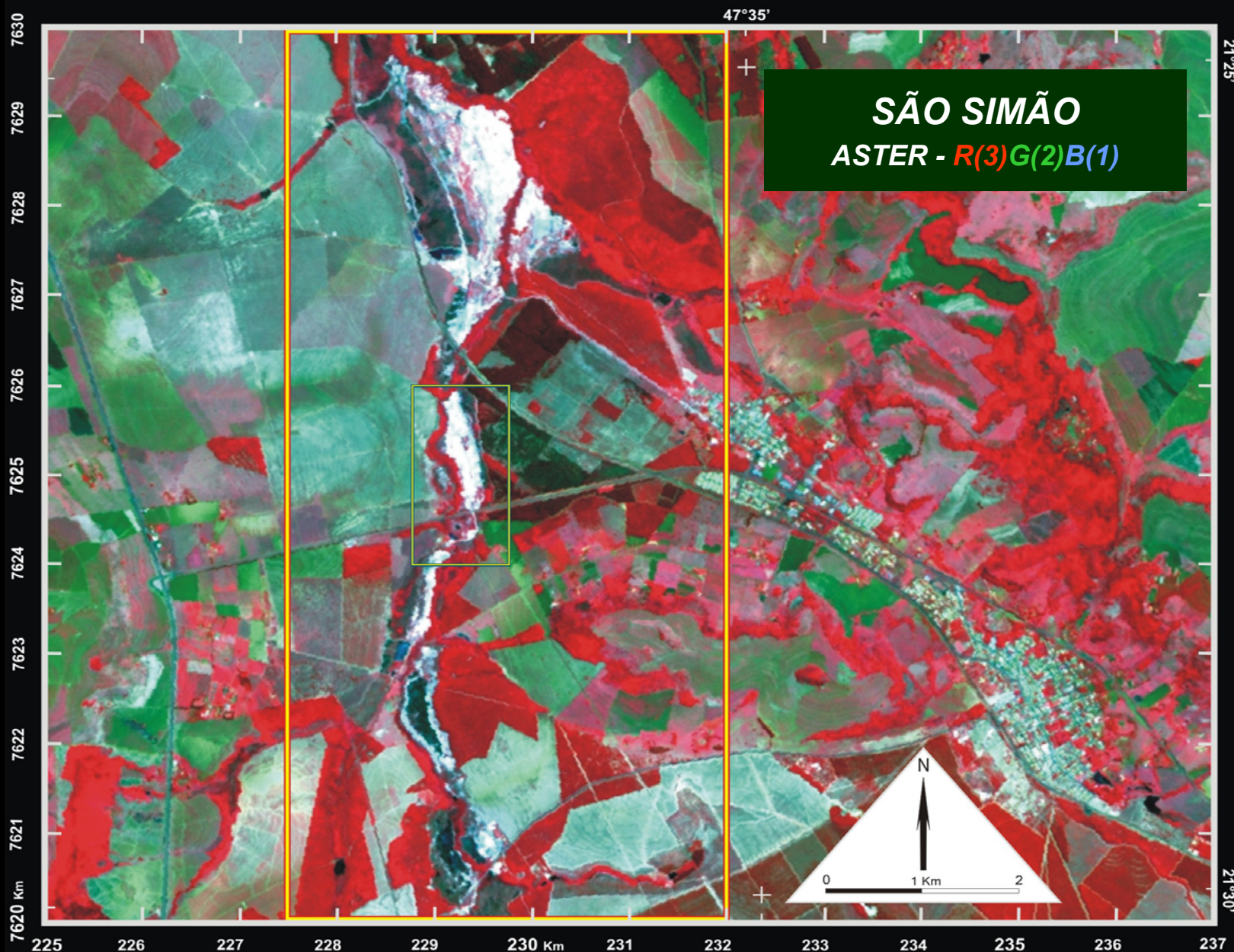
Eliminated Au of -5
April 20, 2006
Aster data classified by Lag_AU.

EXPLORAÇÃO MINERAL

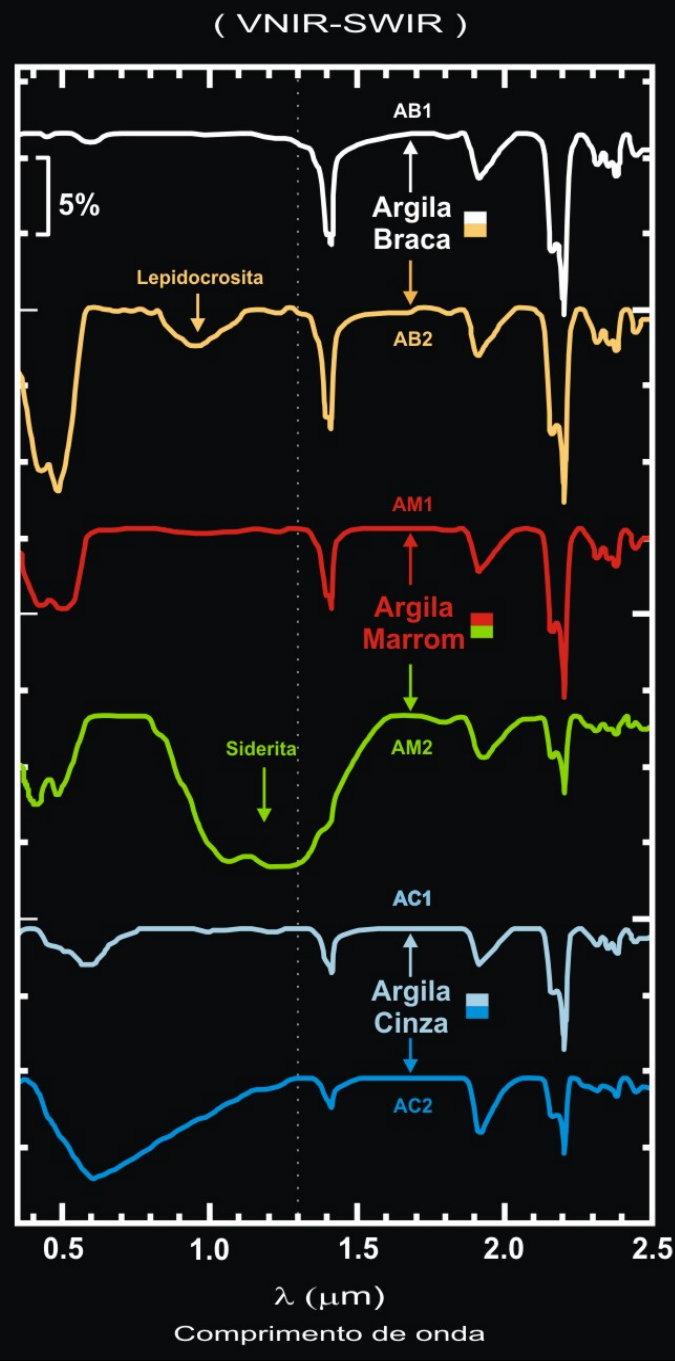
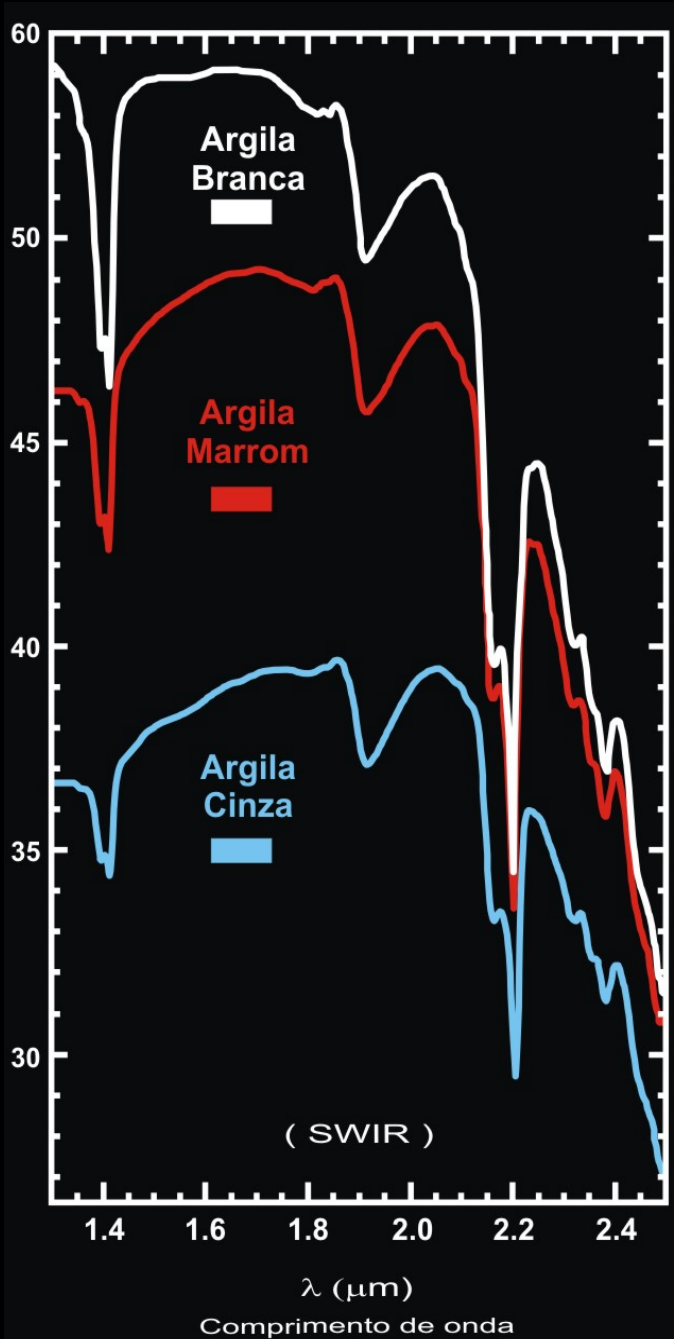
Só... METAIS ?



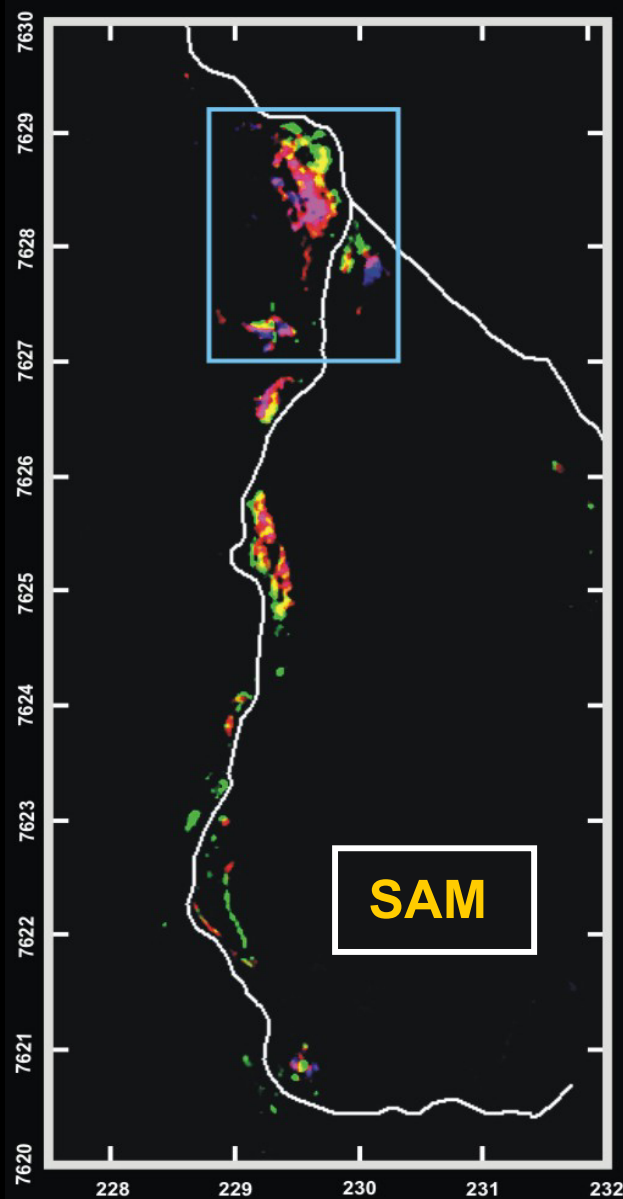
MAPEAMENTO DE ARGILAS CERÂMICAS (Ball-Clay, SP)



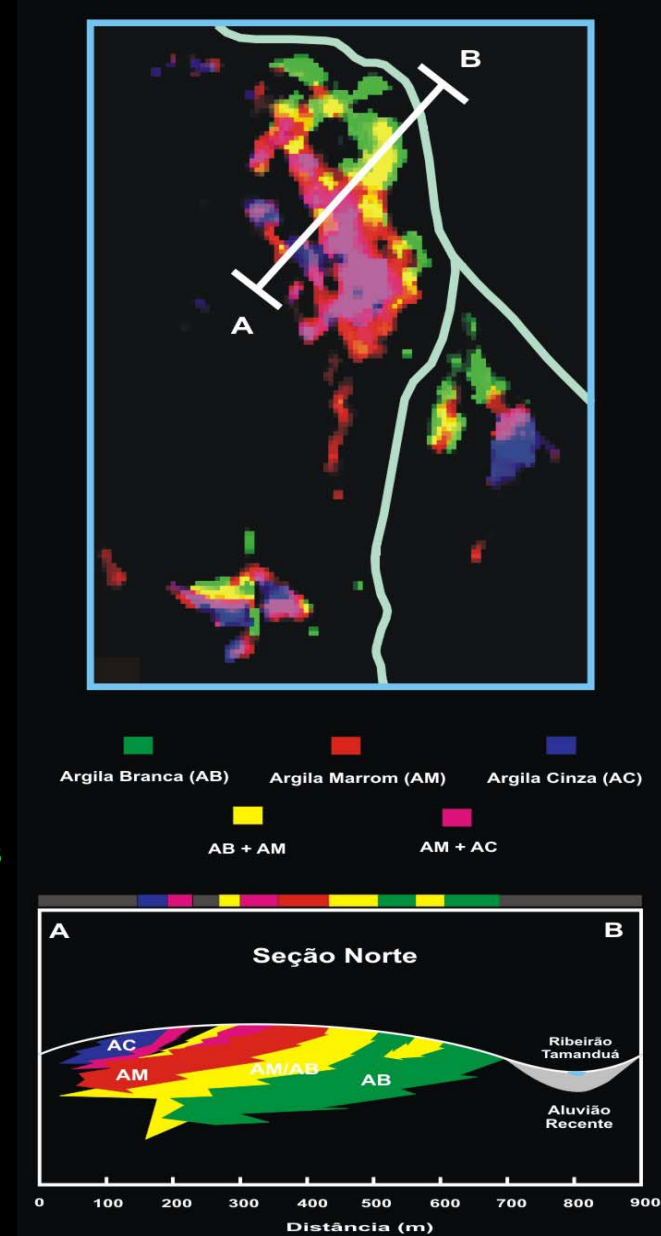
JSENNNA



TIPOLOGIA



Juliano Senna



JSENNÁ

JSENNA MAPEAMENTO DE ARGILAS DE USO INDUSTRIAL (Agalmatolito, MG)

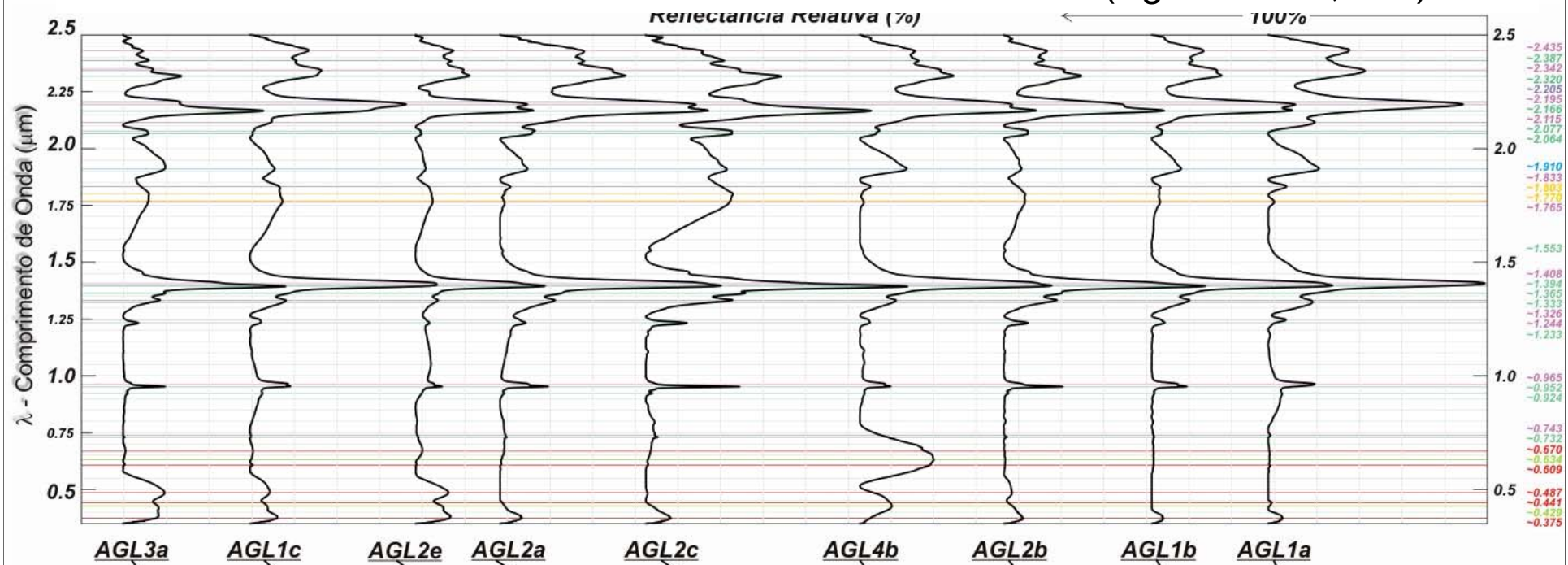
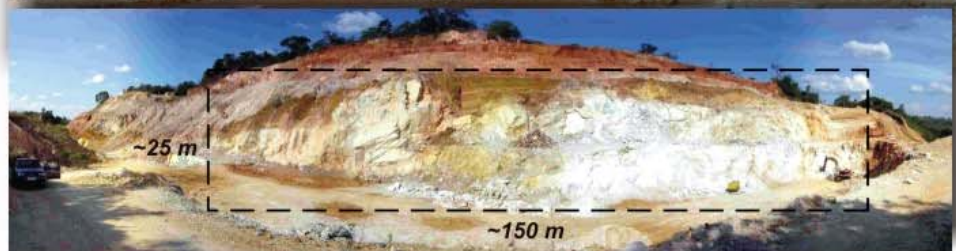
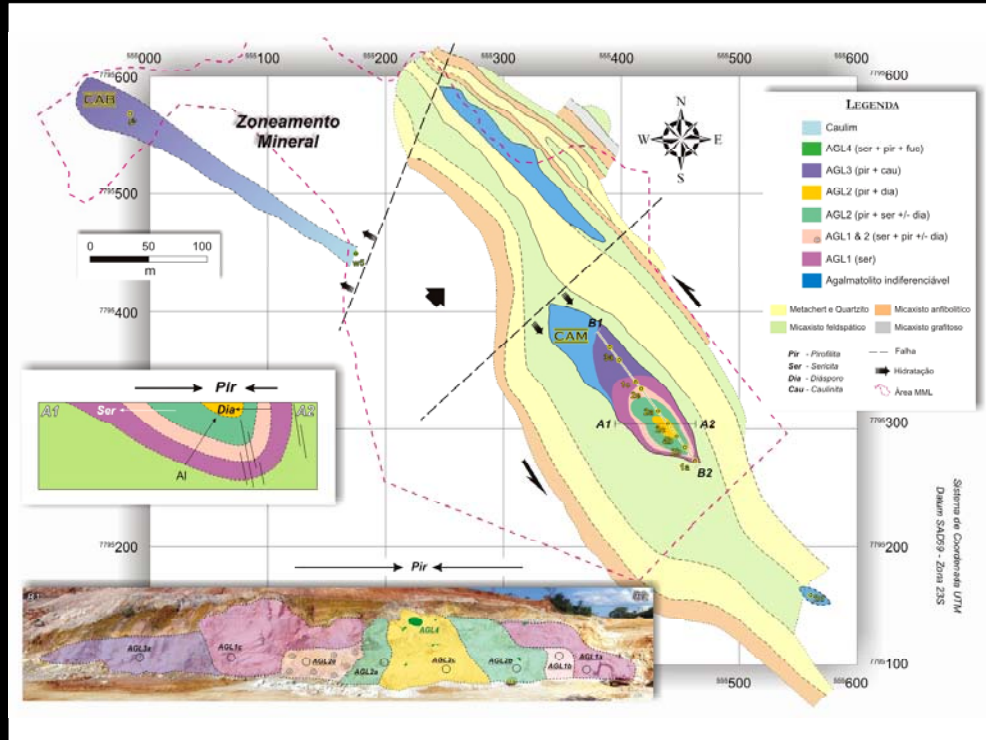
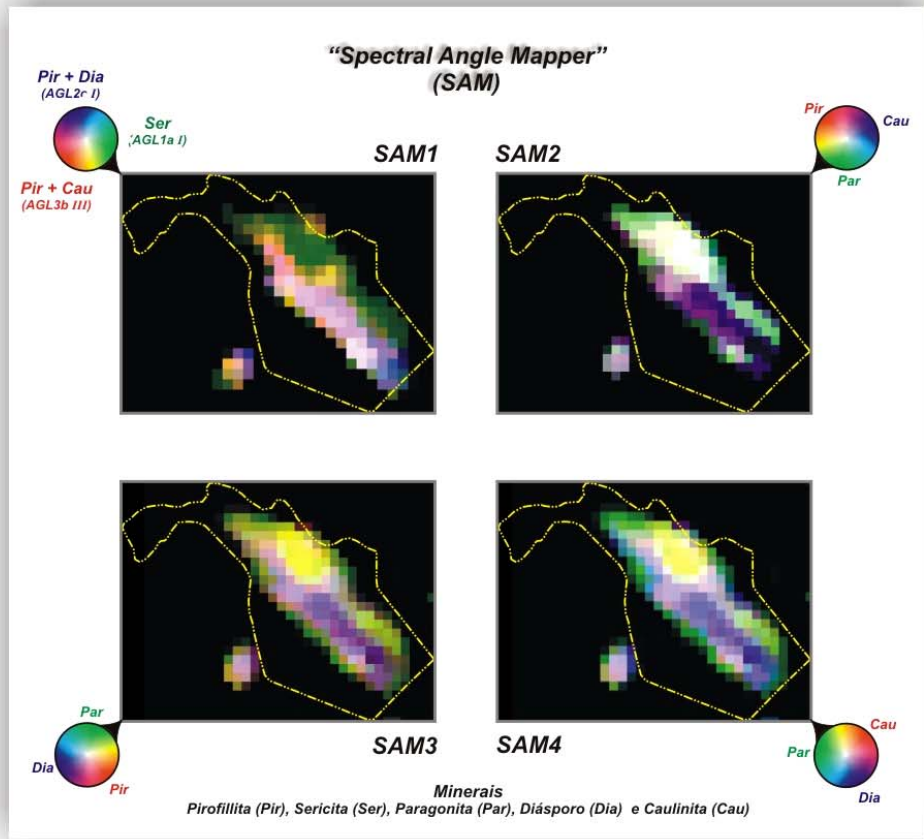
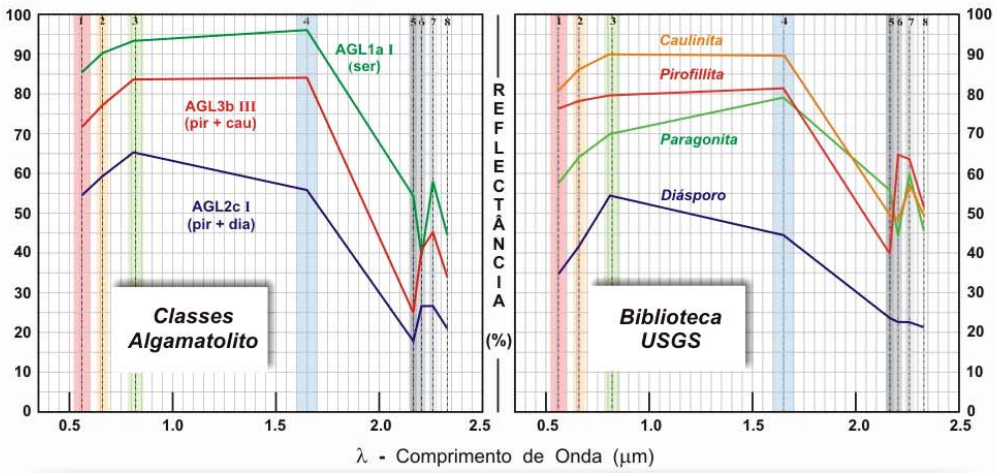


Foto-Seção Espectro-Mineralógica Corpo Agalmatolítico Maritaca (AGL - CAM)



Feições Espectrais		
— Sericita	— Pirofillita	— Cr ³⁺
— Diásporo		— Fe ²⁺ /Fe ³⁺
— Caulinita		— H ₂ O

Espectros de Referência

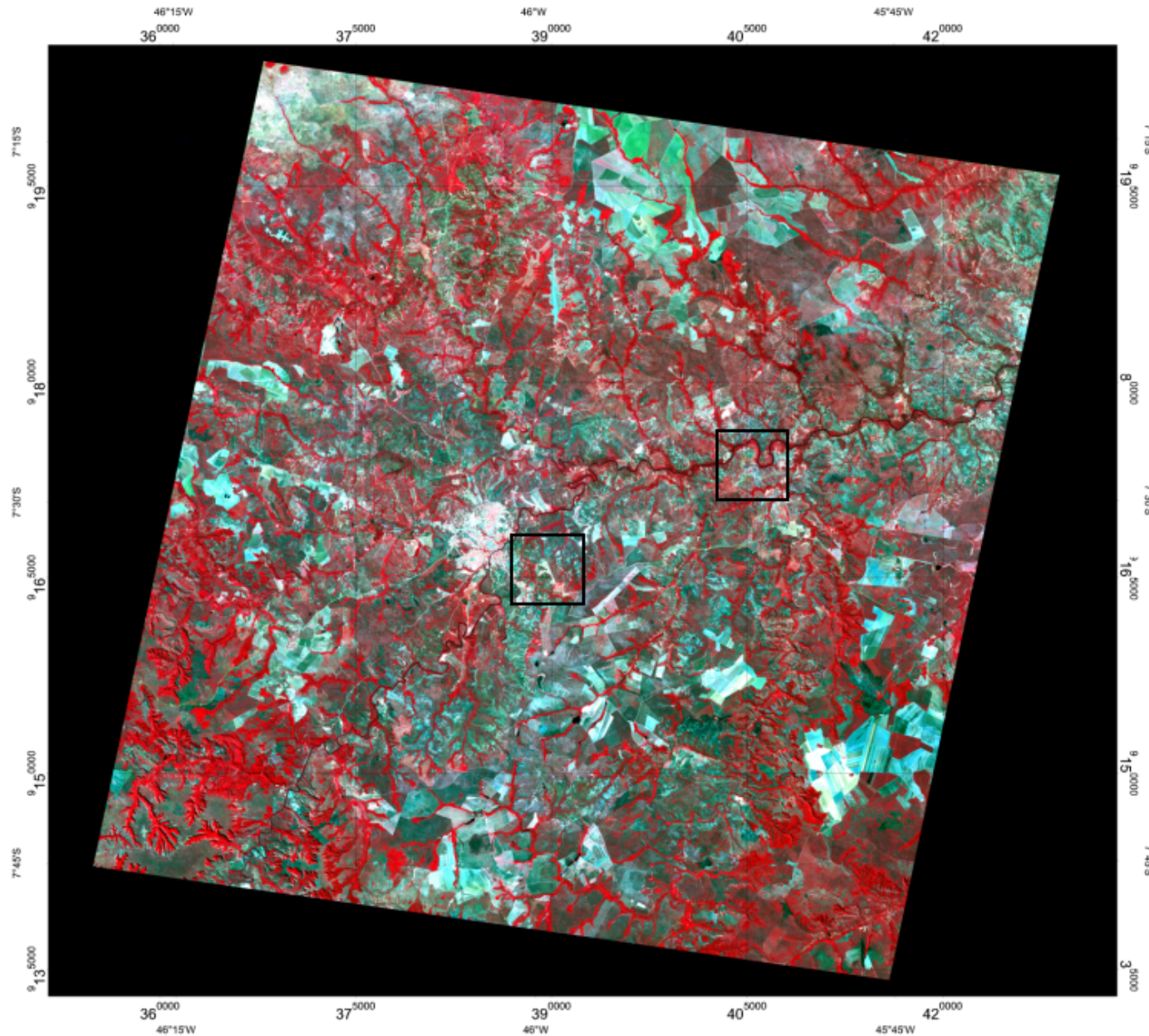



JSENNÁ

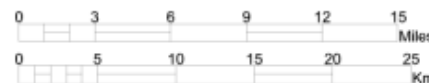
MAPEAMENTO DE CARBONATOS

(matéria prima de
cimento)

(sul do Maranhão)



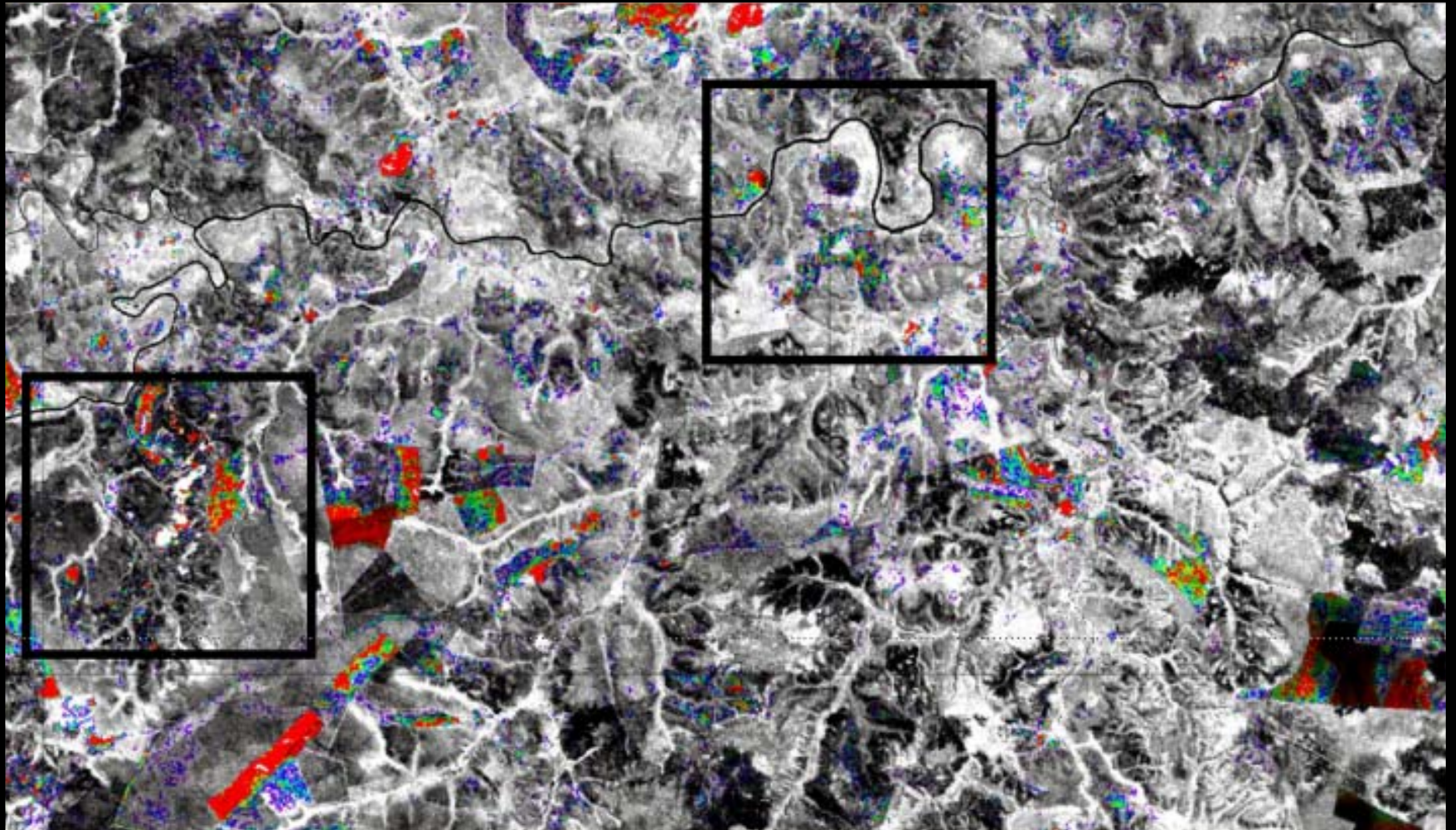
 áreas de coleta
de amostras
de referência



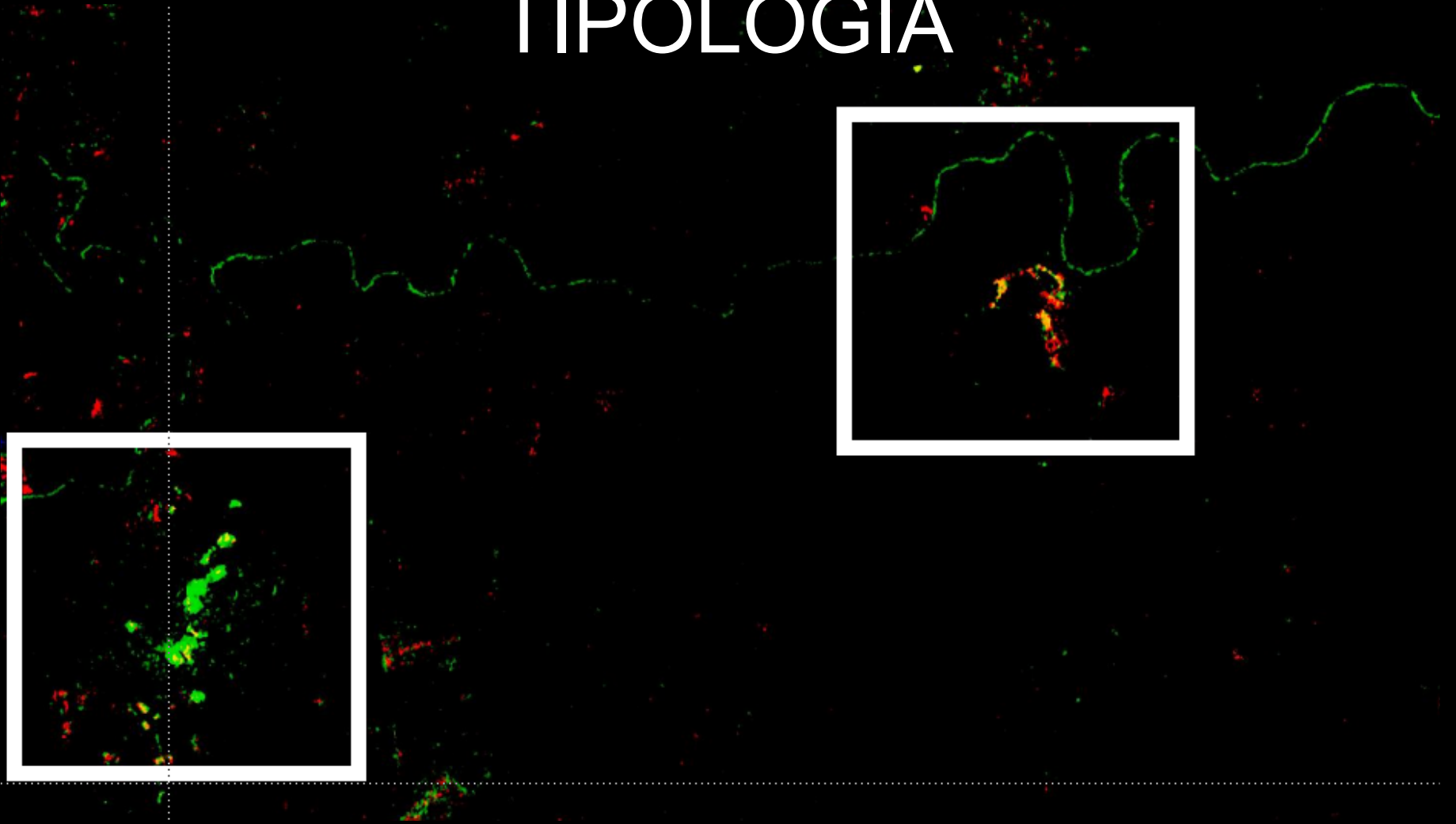
Map Scale 1:100,000

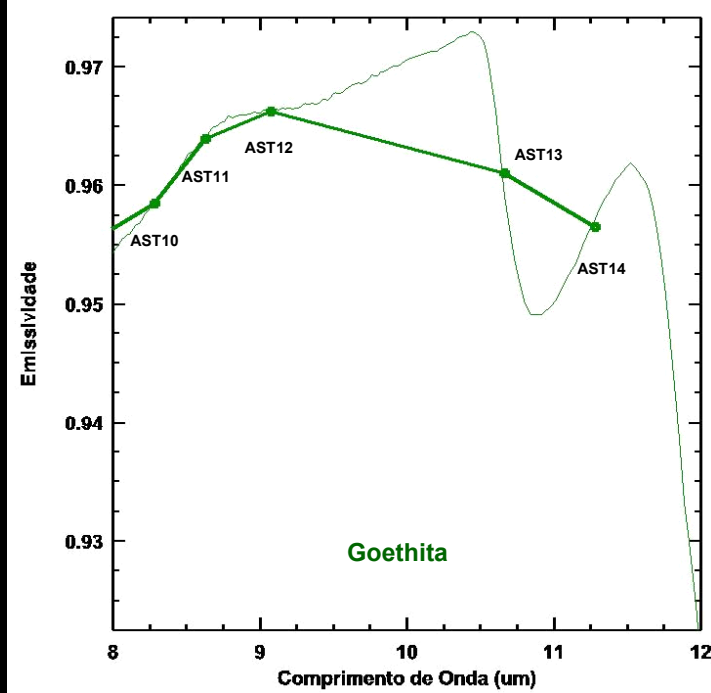
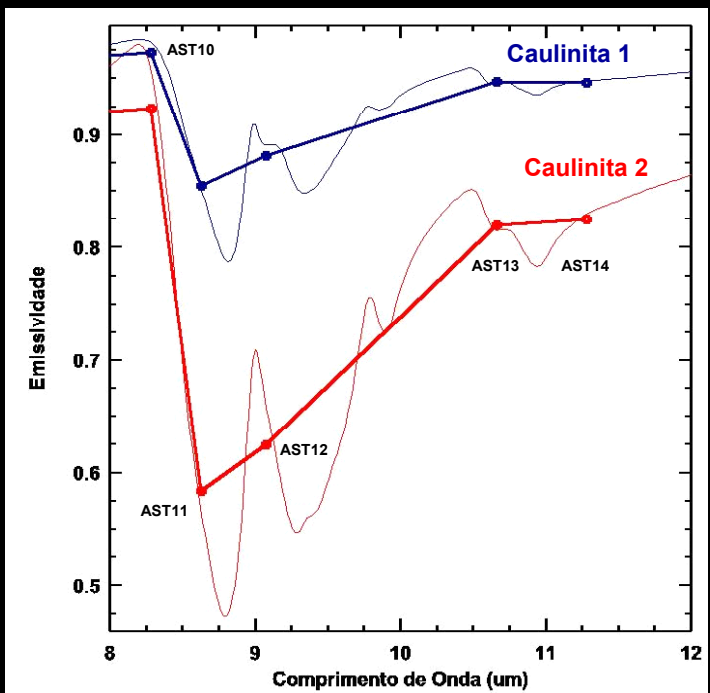
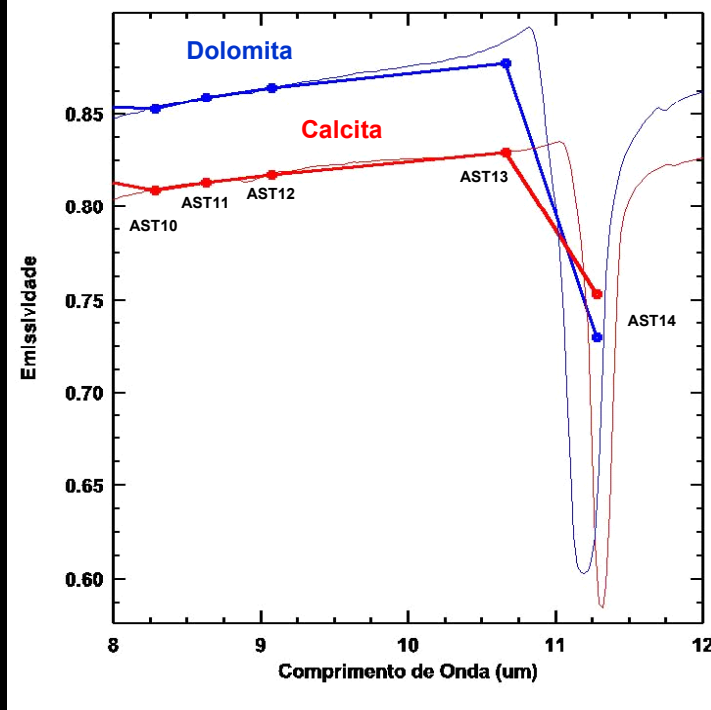
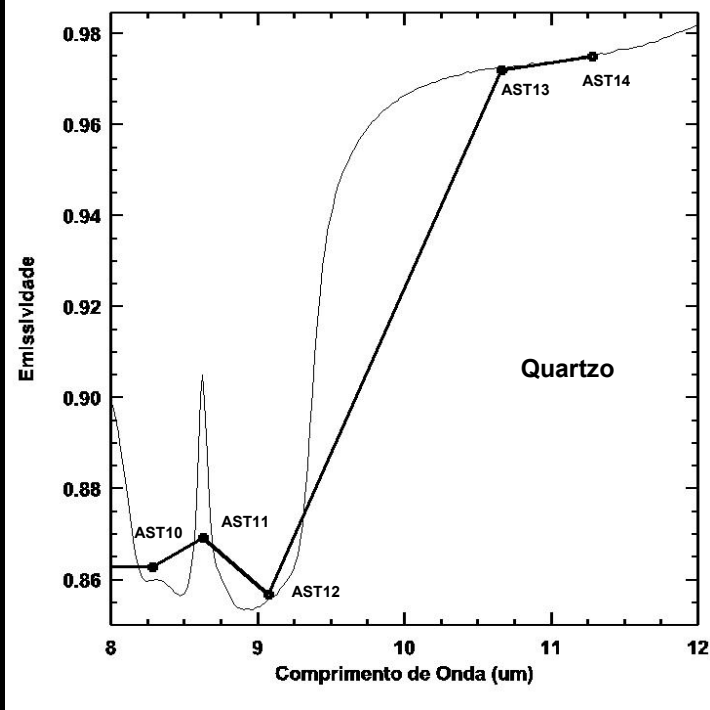
ASTER/TERRA
COMPOSIÇÃO COLORIDA
FALSA-COR
BANDAS 321 (RGB)

ABUNDÂNCIA



TIPOLOGIA





DEPÓSITOS
CARBONATOS
& CRISTAL de
ROCHA
(quartzo)

ASTER TIR

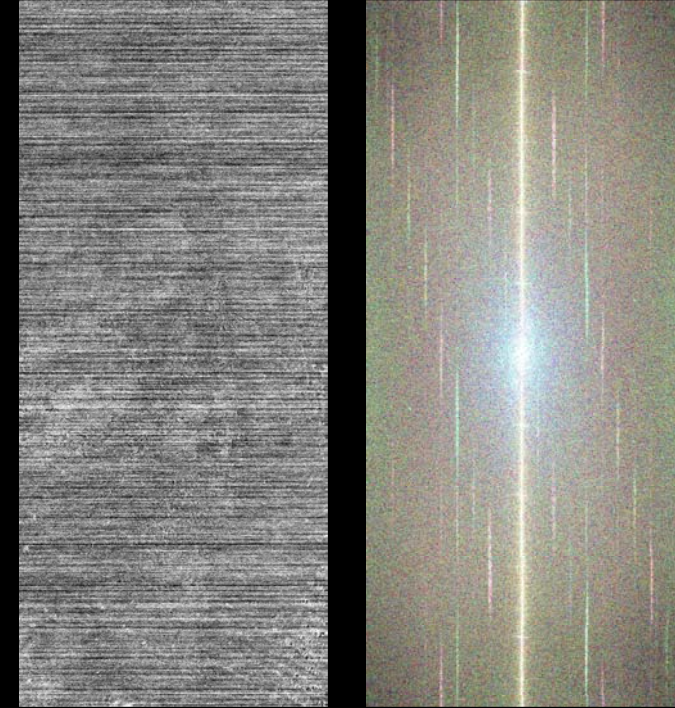
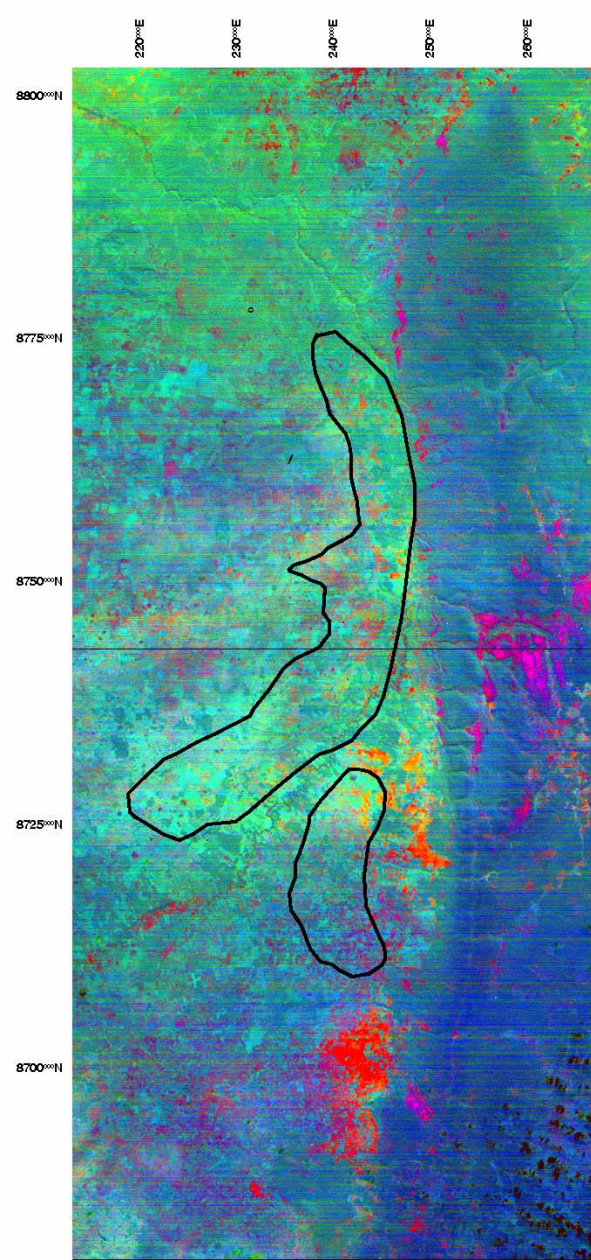
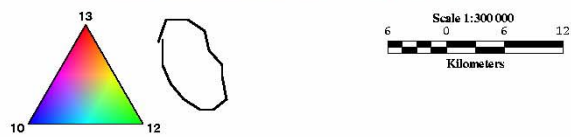
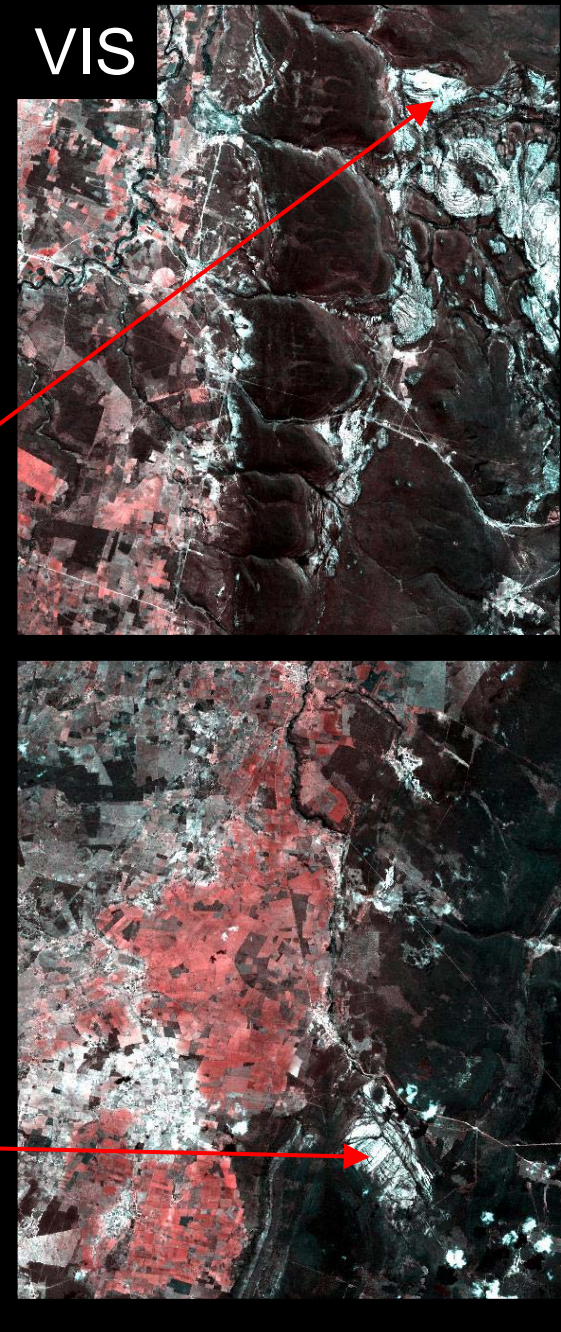
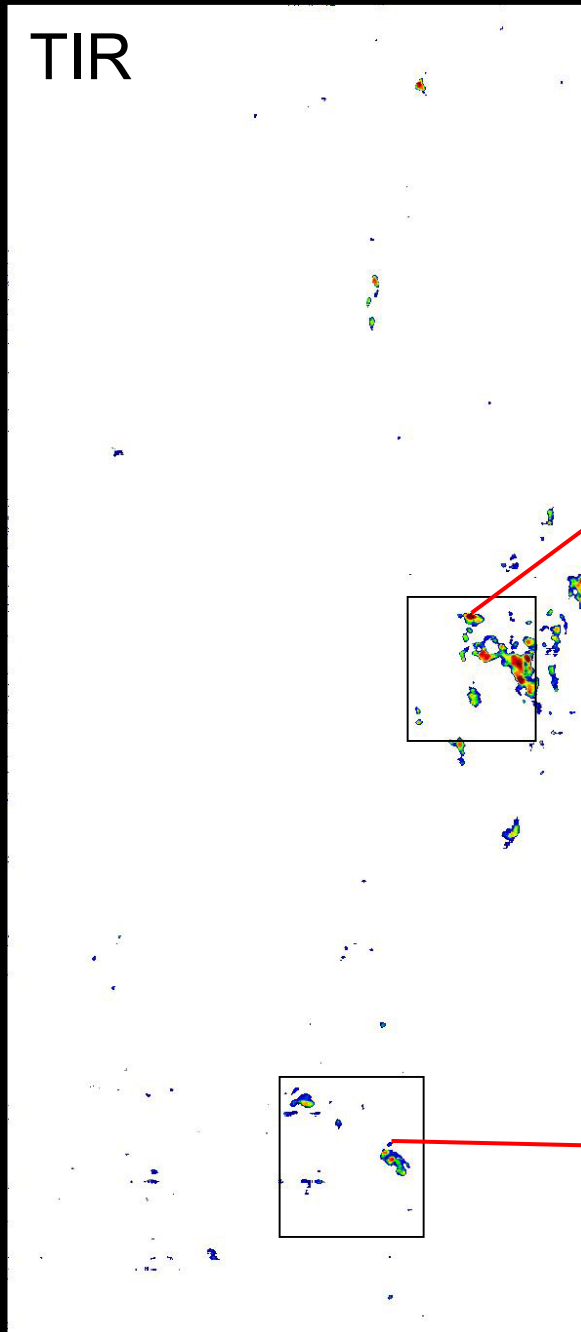
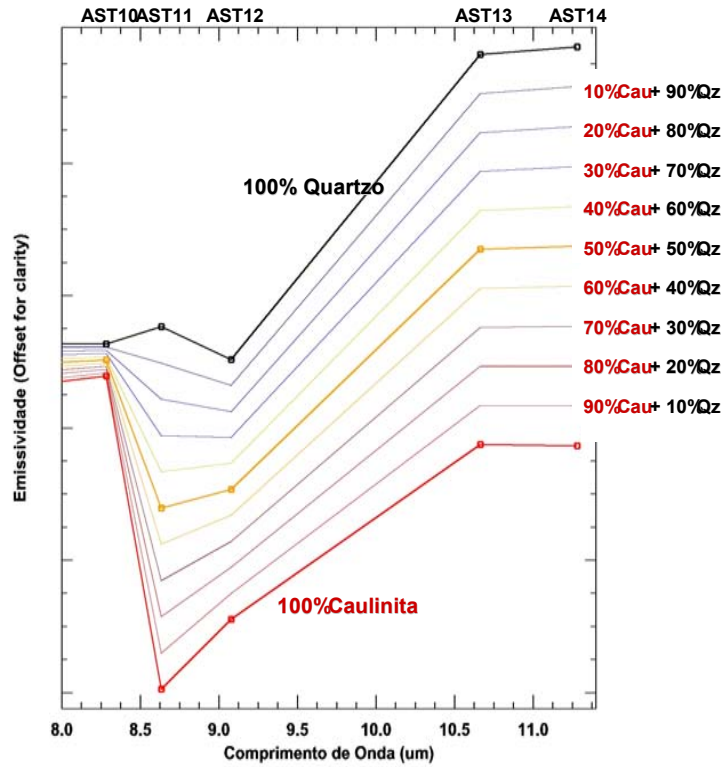
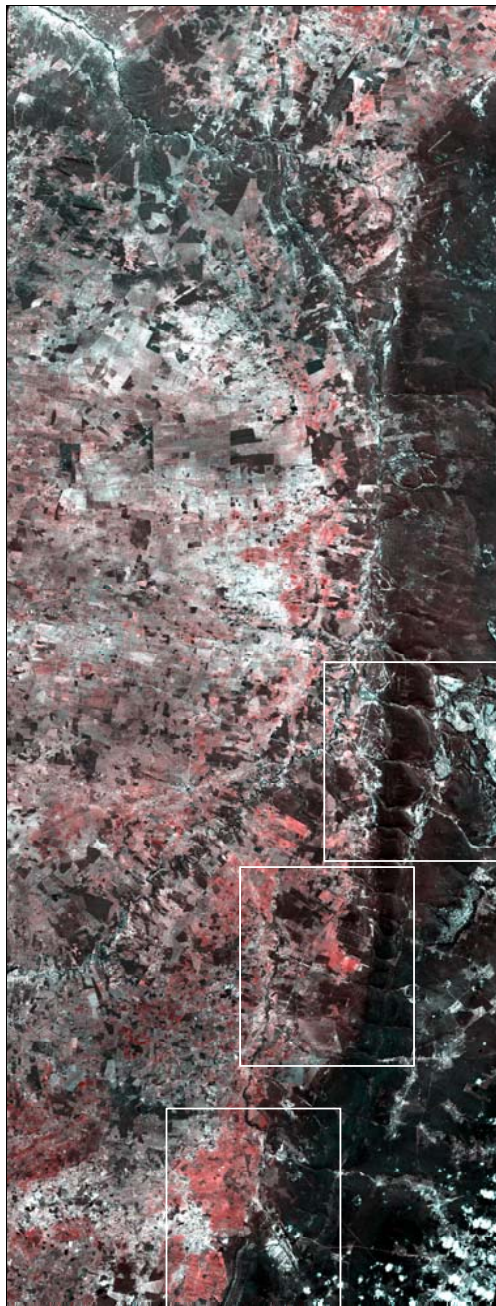
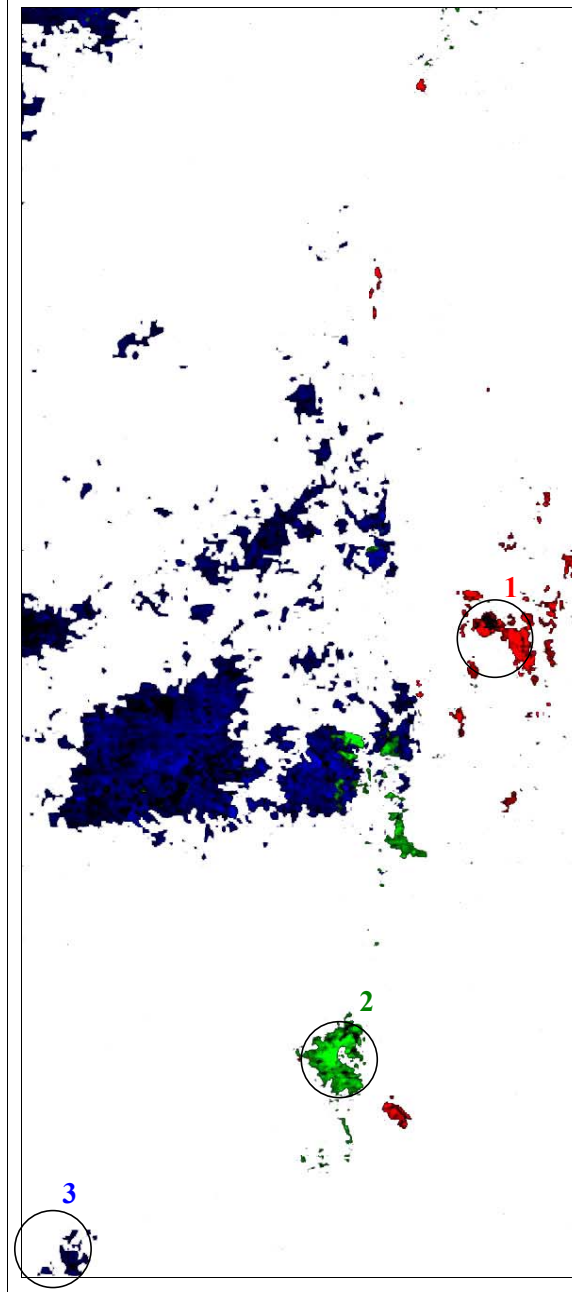
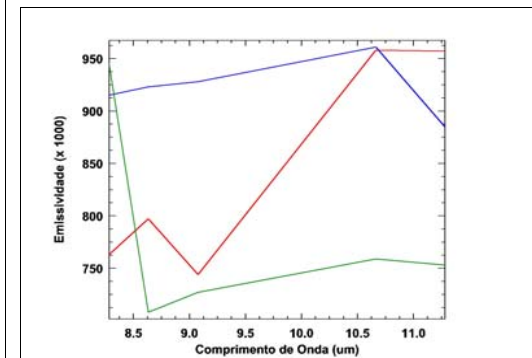


Ilustração dos complexos ruídos presentes nas bandas termais do ASTER da área de estudo. (a) imagem MNF - as componentes de ruído, decorrelacionadas entre as 5 bandas termais, foram segregadas. (b) composição colorida das imagens de magnitude obtidas a partir da aplicação de uma Transformada Fourier às bandas MNF mais ruidosas, entre as cinco calculadas.

(a) Composição colorida falsa cor das bandas AST13, AST12, AST10 em RGB. (b) Resultado da aplicação do realce por decorrelação ao triplete (a). Polígonos = áreas de gossans conhecidos na bacia de Irecê



Resultado obtido com a técnica de pseudo-razão aplicada as bandas AST11 e AST12, visando a detecção de sílica (quartzo), separadamente de argilo-minerais (caulinita). (a) imagem da pseudo-razão em pseudo-cor (após ajuste de histograma e filtragem com filtro de mediana de 5 x 5 pixels). Note que as exposições de quartzitos do Supergrupo Espinhaço, que aparecem como áreas esbranquiçadas em (b) e (c), são mapeadas nesta pseudo-razão.

(a)**(b)****(a)**

(a) *Endmembers* (espectros de emissividade) derivados da aplicação, aos dados do ASTER, convertidos para emissividade, das técnicas MNF, PPI, visualização n-dimensional e separação por *clustering*. Esses espectros são extremamente análogos aos de **quartzo (vermelho)**, **caulinita (verde)** e **carbonatos (azul)** derivados na biblioteca JHU (*cf.* Figuras 6.4 e 6.5). (b) Composição colorida (com histograma ajustado e filtragem com filtro de mediana de 5 x 5 pixels) das três bandas derivadas da transformação MNF - MNF **b**, MNF **c**, MNF **a** da Figura 6.12 em RGB. Os círculos nesta imagem marcam setores onde vários pixels mais puros de **quartzo (1)**, alguns de **carbonatos (3)** e raros de **caulinita (2)** foram detectados pelos métodos utilizados.

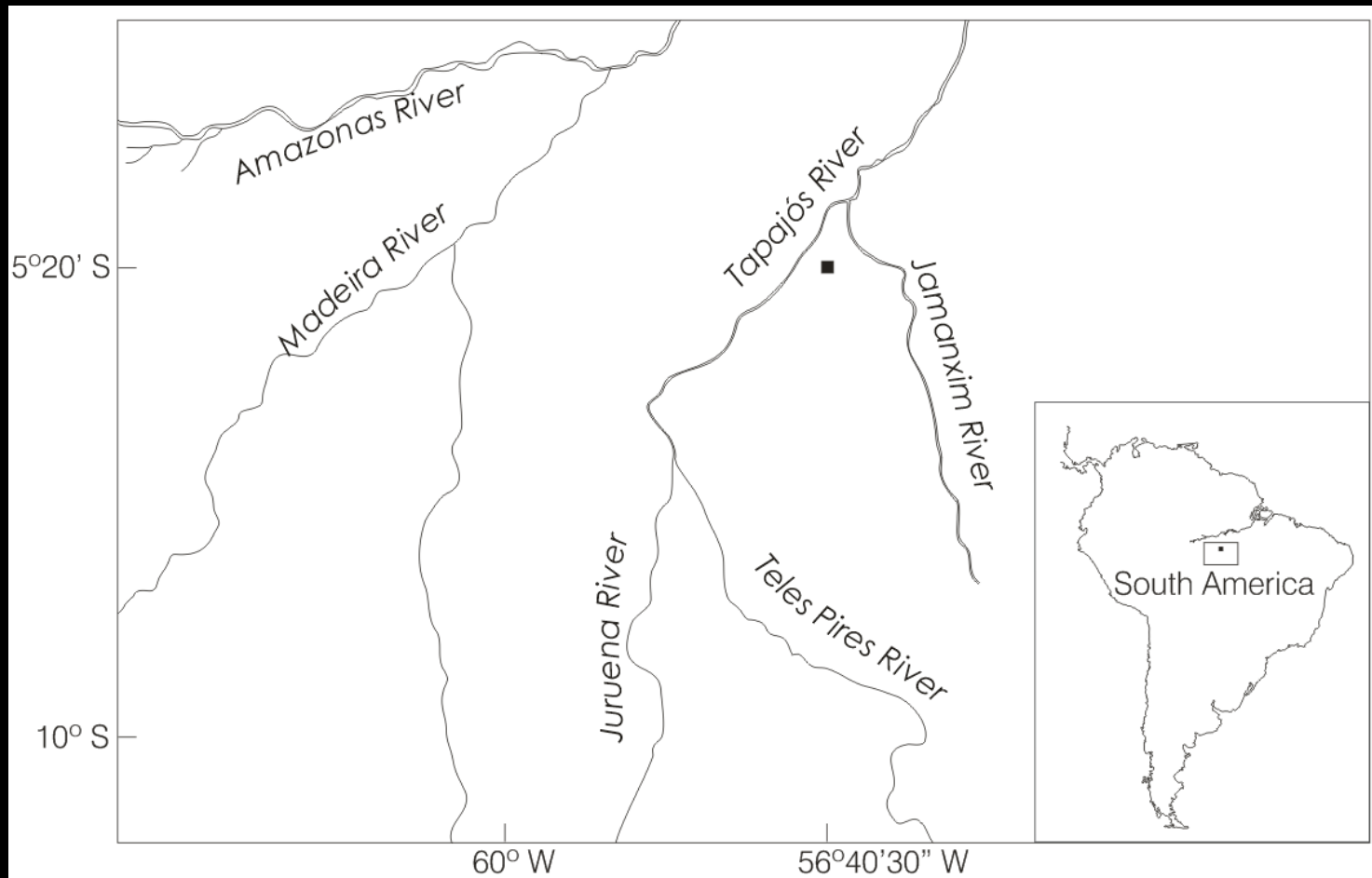
Tapajós, Amazônia

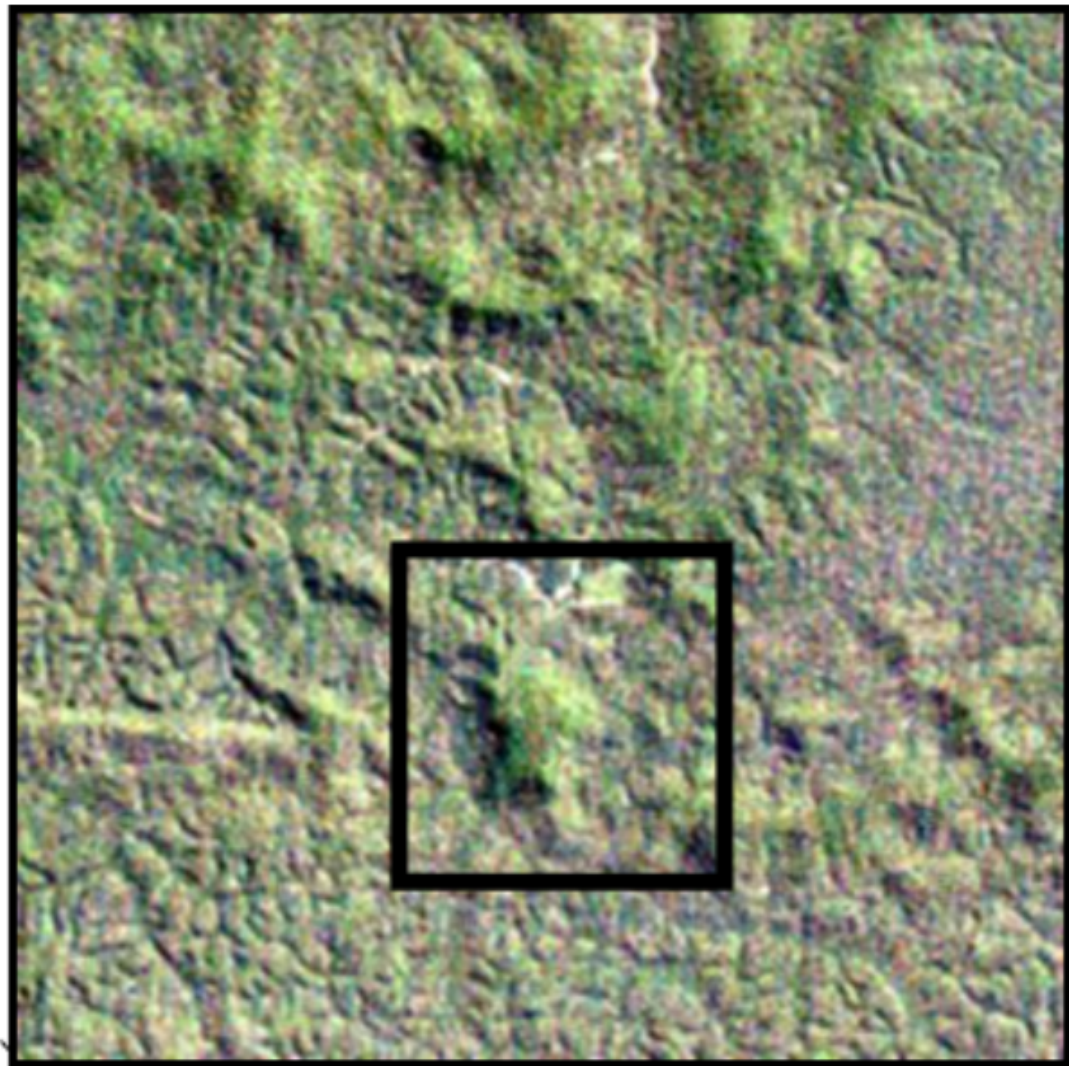
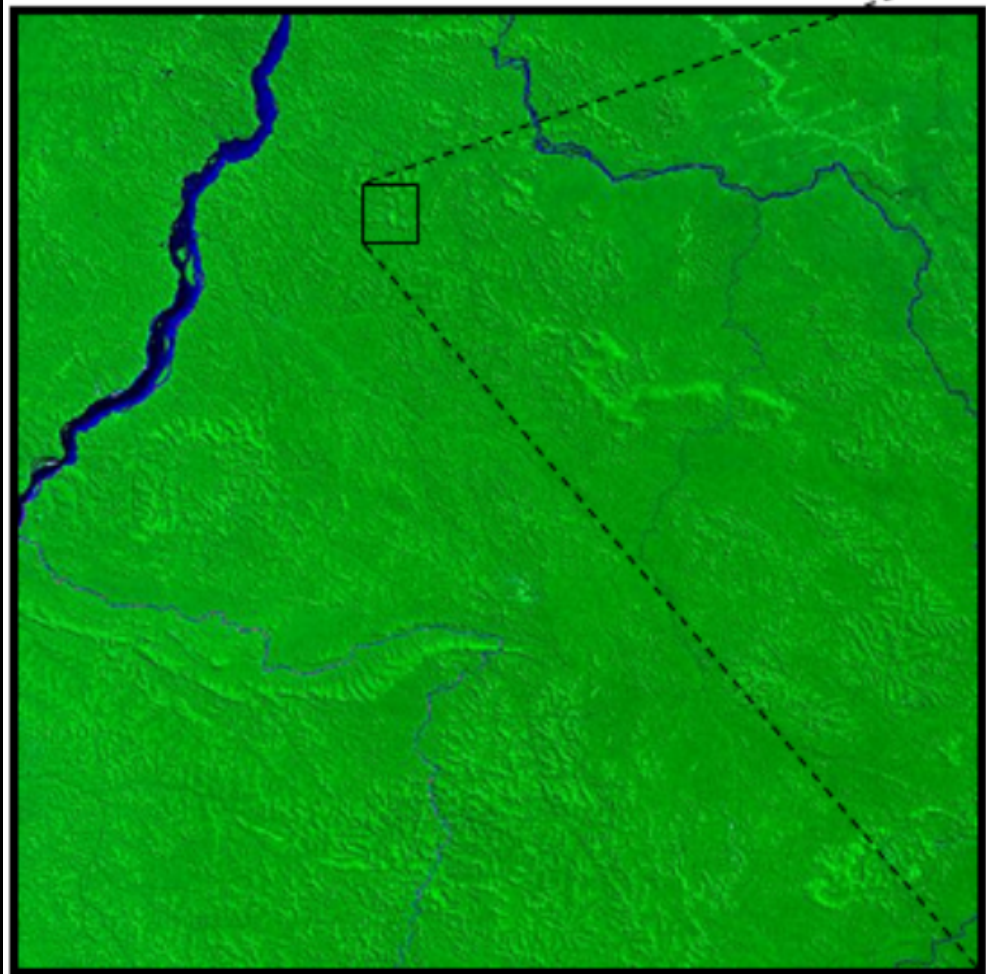
GEOBOTÂNICA POR SENSORIAMENTO REMOTO

DETECÇÃO DE FÁCIES DE ALTERAÇÃO HIDROTHERMAL

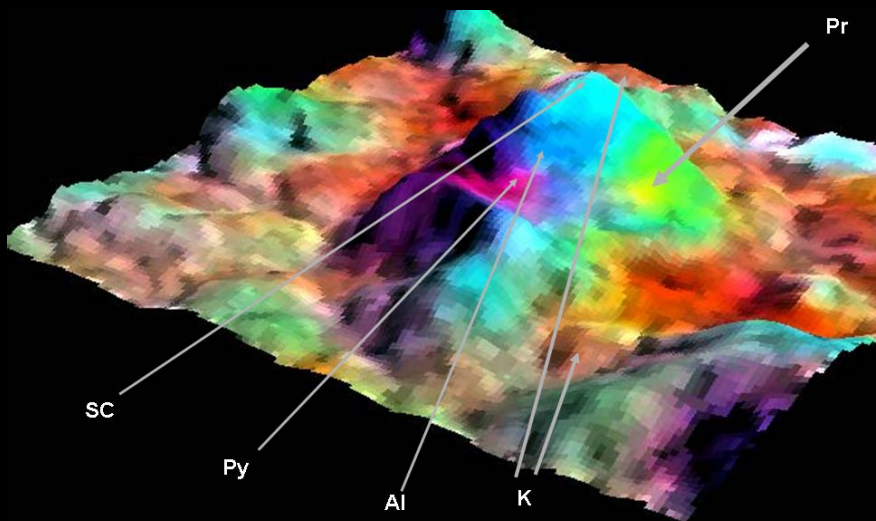
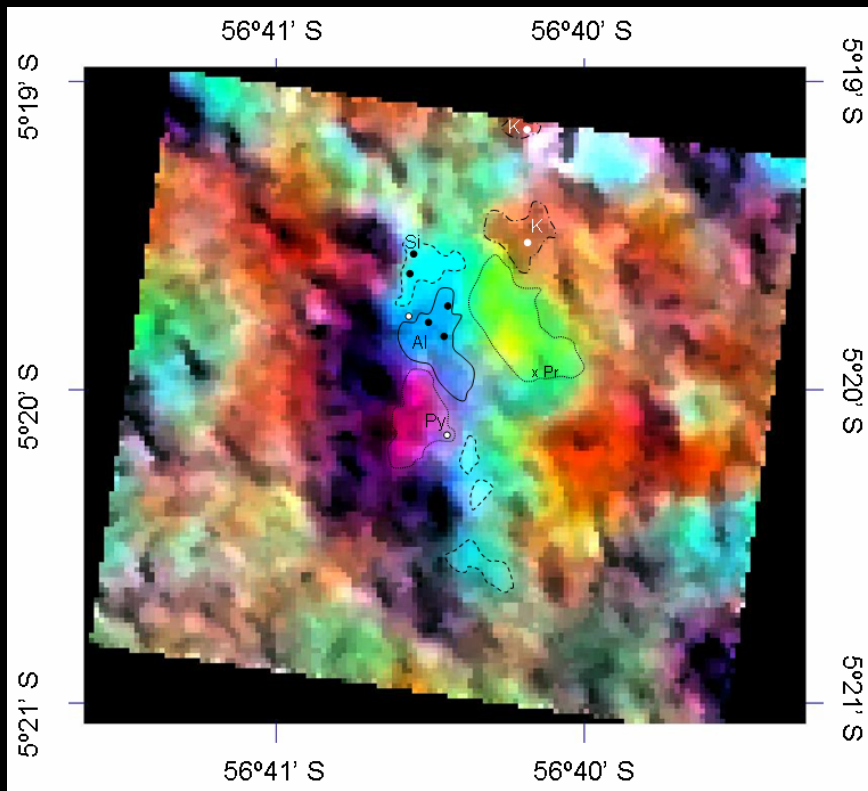
TIR ALMEIDA

DEPÓSITO AURÍFERO EPITERMAL *HIGH SULFIDATION*

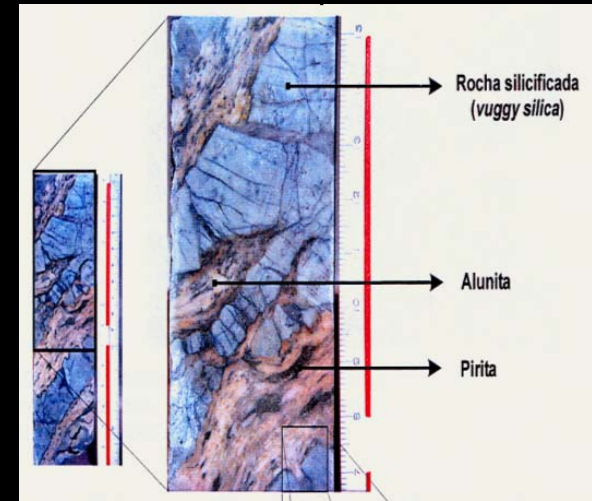




TIR ALMEIDA



Si - Sílica cap: formado por quartzo microcristalino com vuggy silica e relíquias de drusas, hematita ± pirofolita ± alunita ± sulfetos e relíquias de feldspatos.



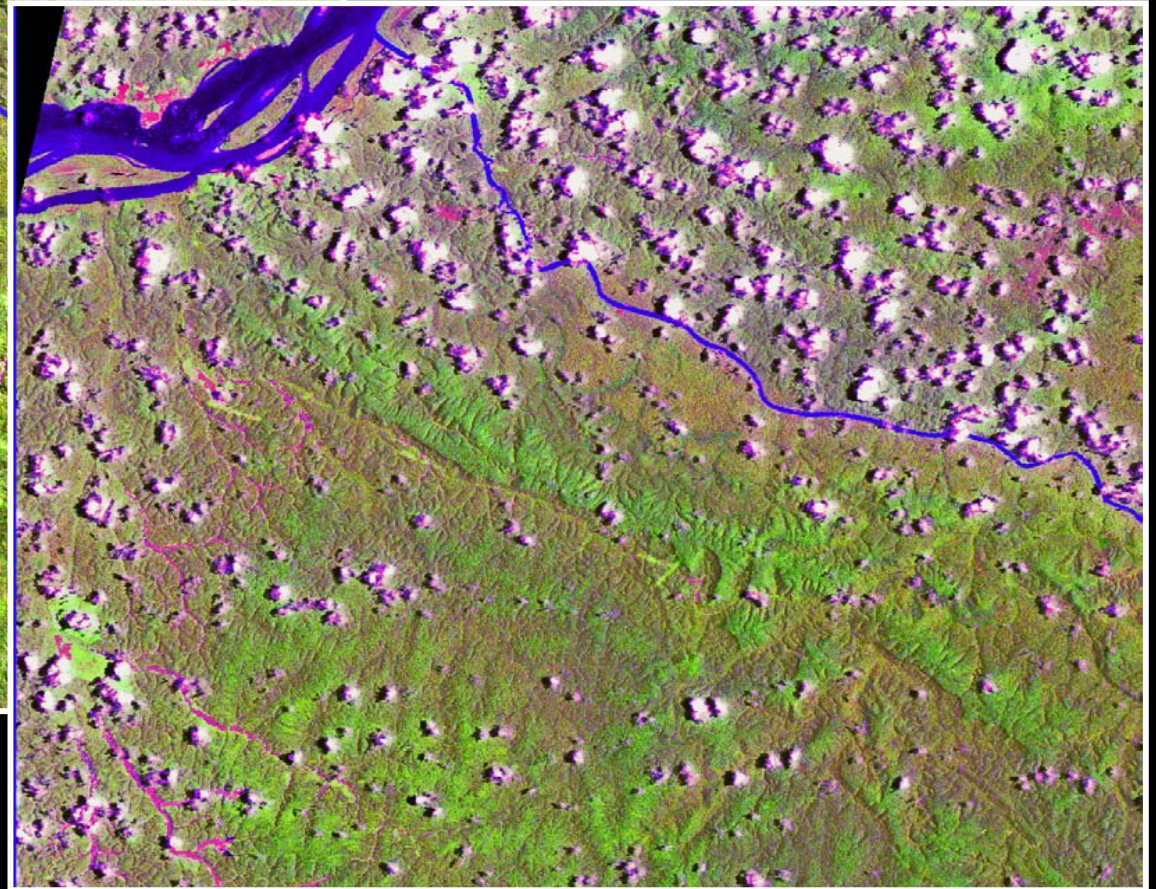
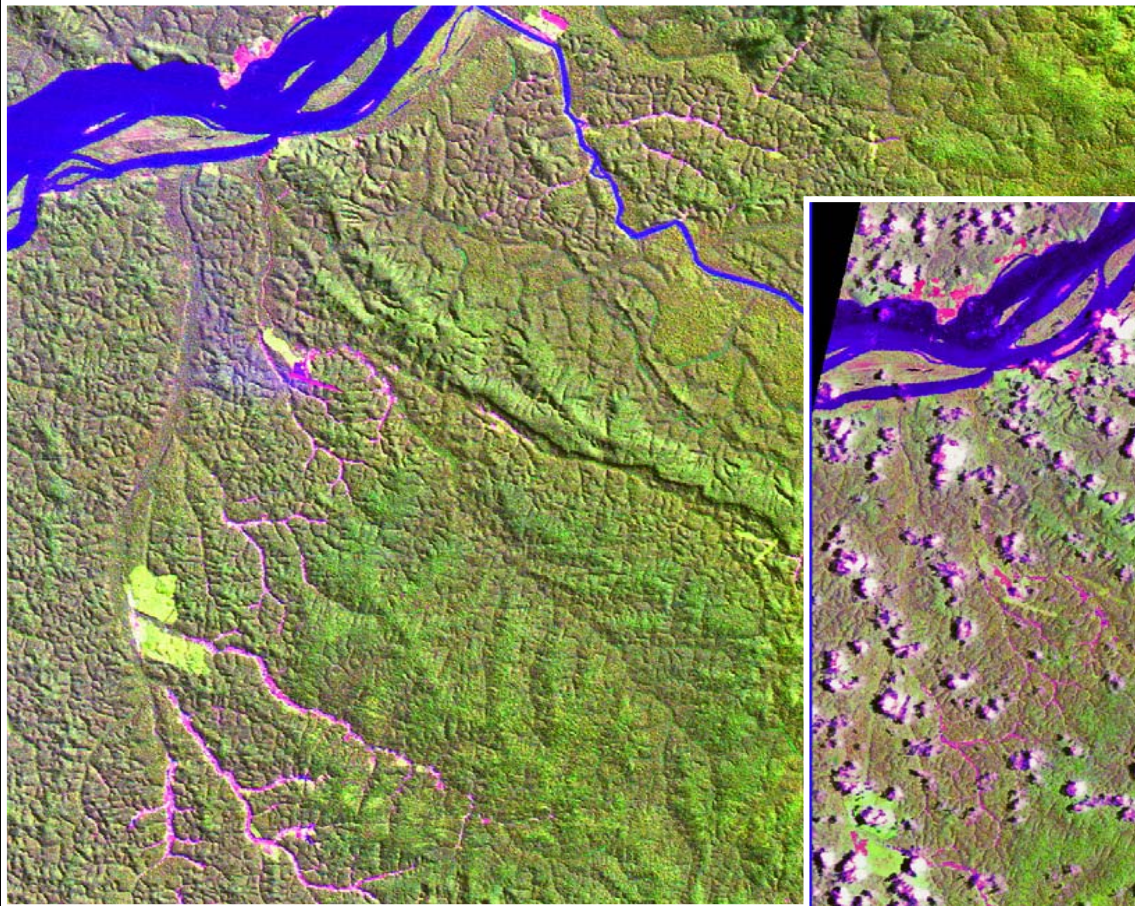
Al - Zona de alteração argílica avançada com pirofilita + andalusita + alunita-natroalunita ± caolinita-dickita ± diásporo ± rutilo ± corindon ± woodhouseita-svanbergita ± pirita com inclusões de enargita-luzonita, calcopirite ± bornita ± covelita ± galena ± esfalerita ± ouro ± prata e cobre nativos.

Py - Zona de alteração argílica avançada com pirofilita, **sem alunite** e sem andalusita. Argilo-minerais são mais abundantes, podendo formar veios de caolinita. Nas bordas das zonas há enriquecimento em argila e sericita.

Pr - Zona de alteração propilítica e sericítica, com clorita + epidoto-clinozoisita + albita ± anfibólio ± carbonato ± titanita ± sulfetos, ou com sericita + quartzo ± sulfetos

K - Granitos com alteração potássica.

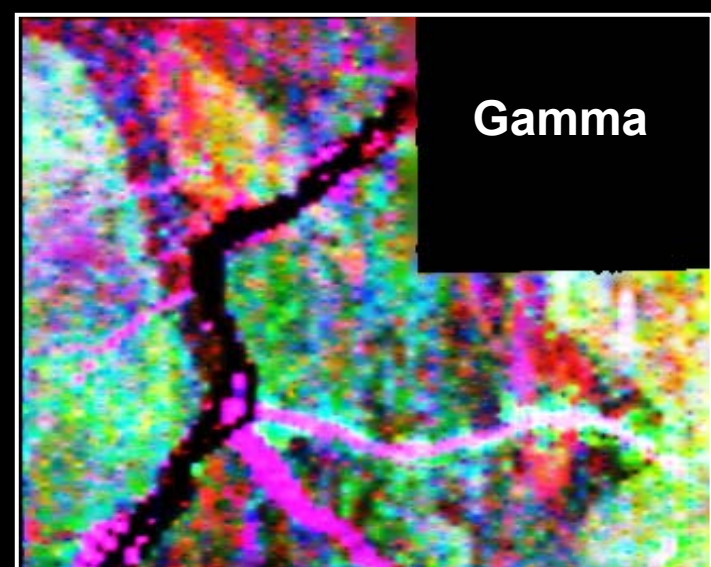
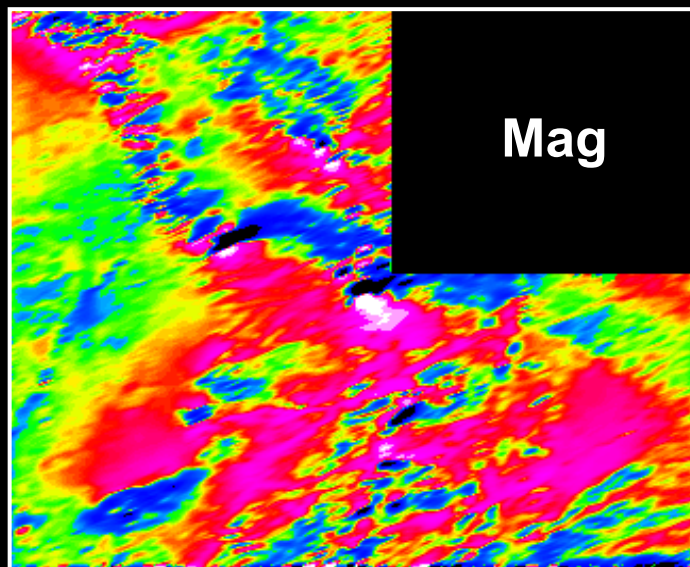
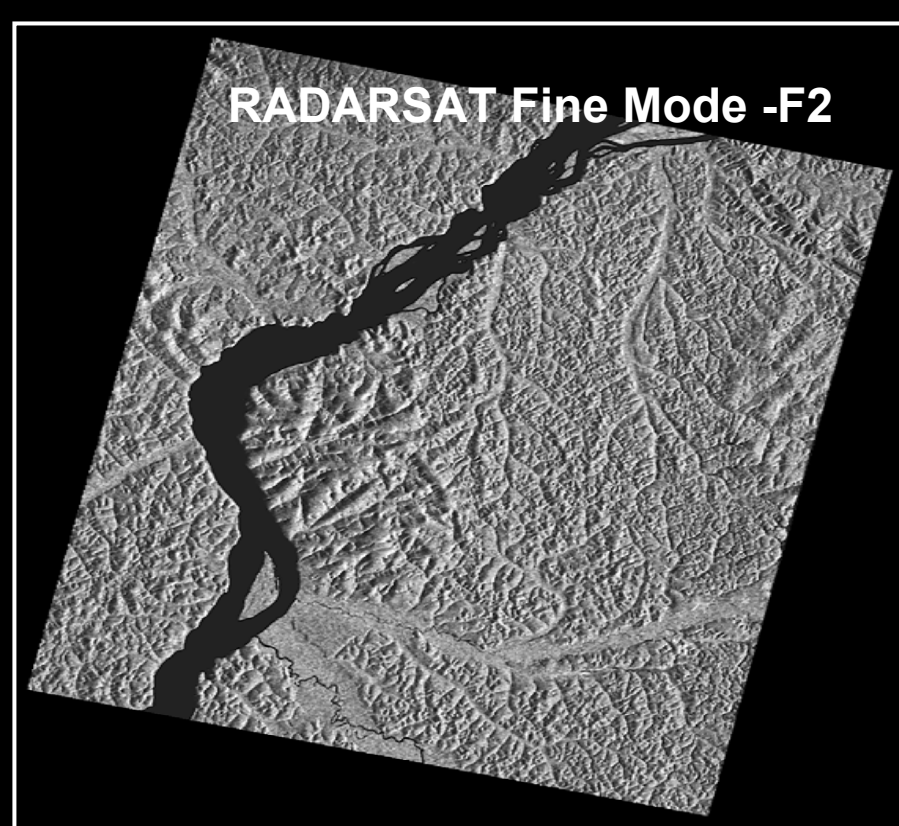
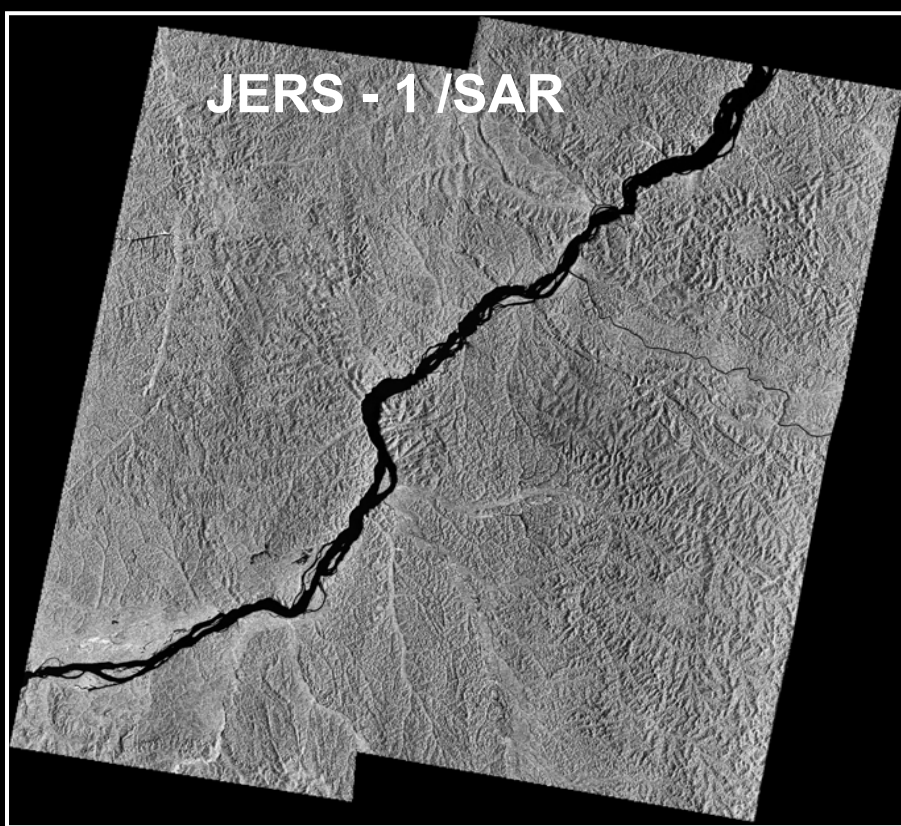
Sensoriamento Remoto Ótico na Amazonia



EXPLORAÇÃO MINERAL

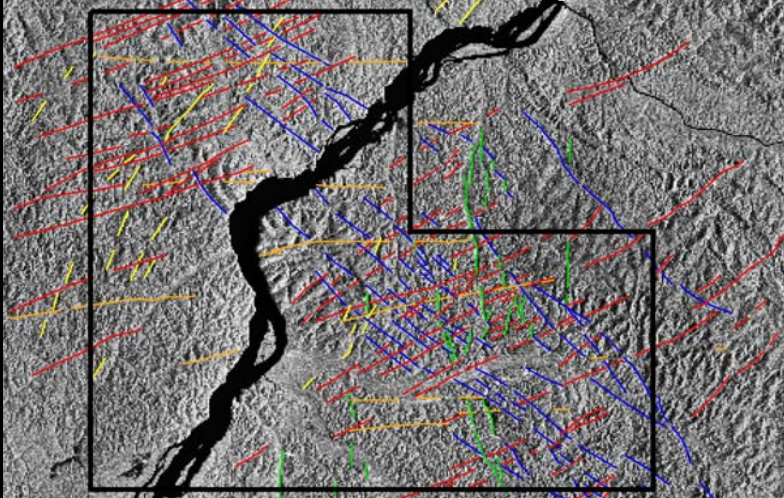


Só... SR ótico ?

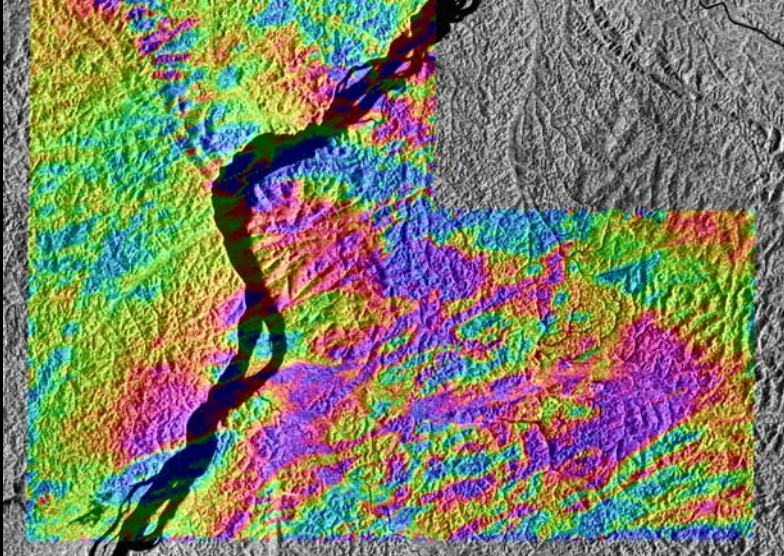


Integração SAR/Aerogeofísica

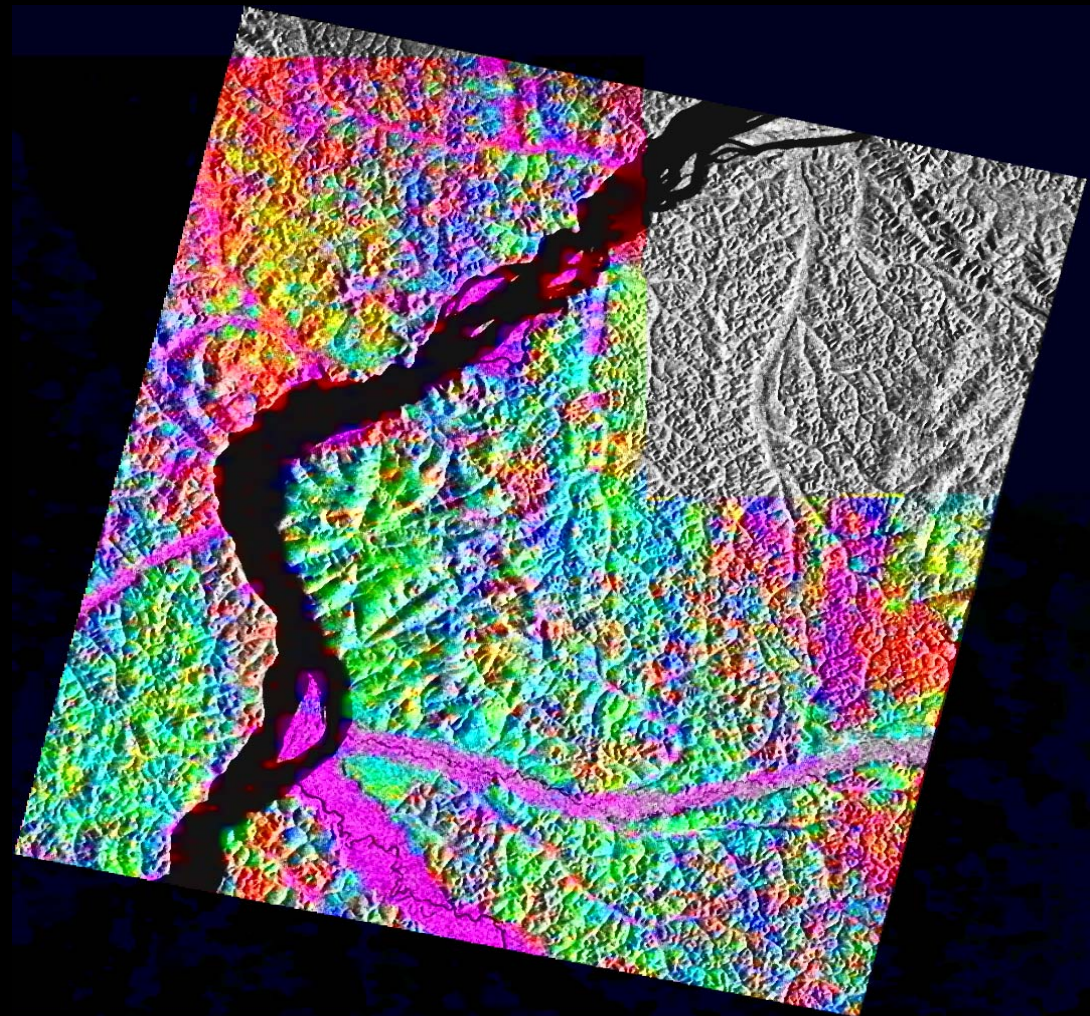
JERS-1 Lineament Interpretation



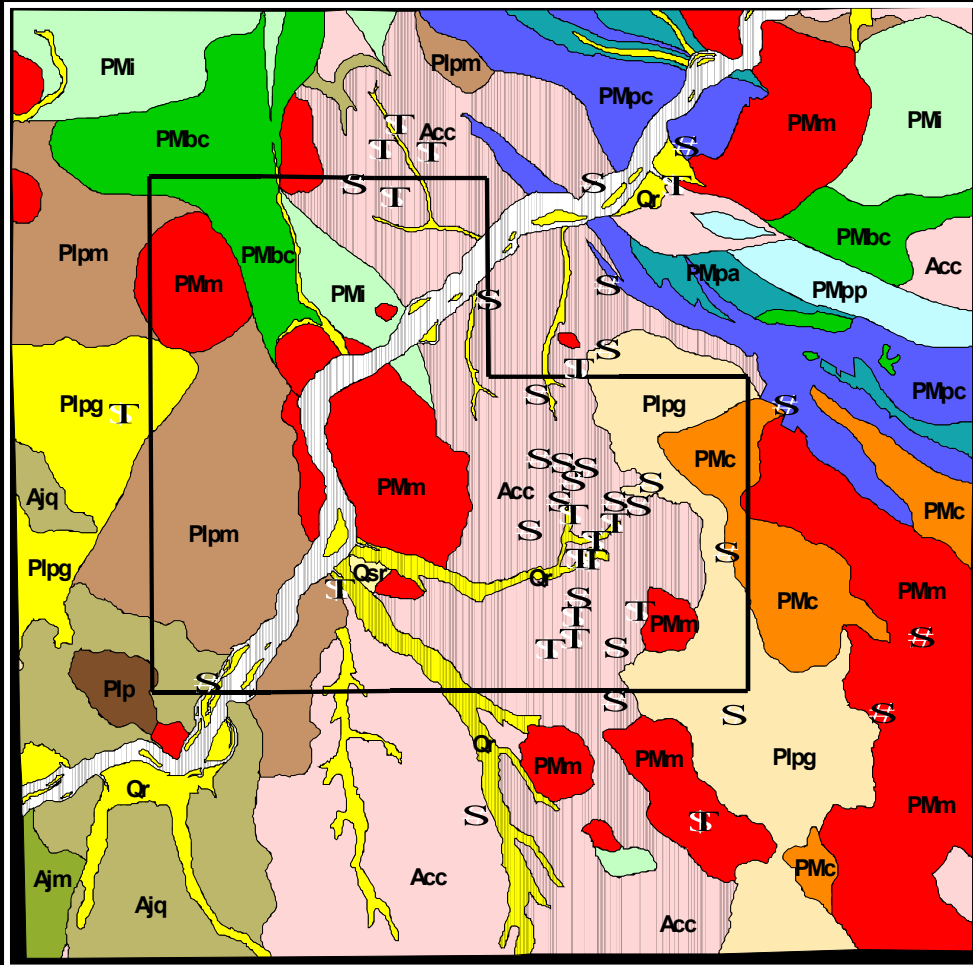
JERS - 1 & Magnetics Integration
(Residual Field Anomaly)



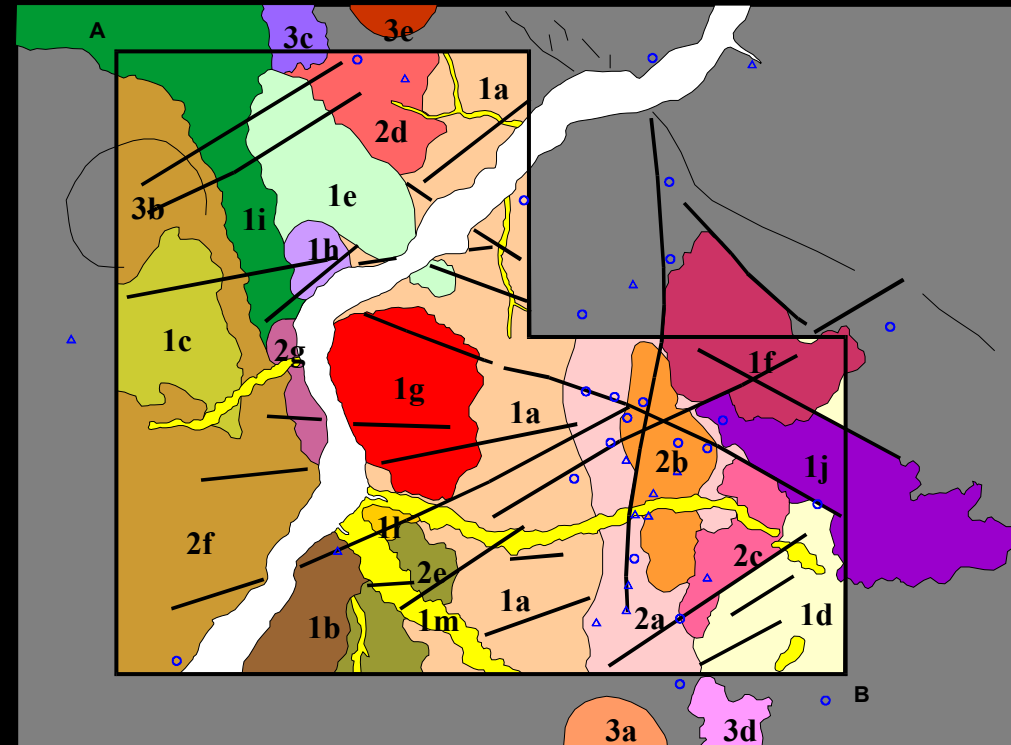
RADARSAT & Gammaspectrometry
(K, Th & U as RGB)



Mapa Geológico - Método Convencional



Mapa Geológico - Método SAR + Gamma



GEOLOGICAL MAP	UNITS	INTERPRETATION MAP	GEOLOGICAL MAP	UNITS	INTERPRETATION MAP
Qr	1m	1m	PMi	1e	1e
Qsr	1l	1l	Plpm, PMc	1f	1f
PMc, Plpg, Acc	1j	1j	Plpm	2f	2f
PMbc	1i	1i	Plpm, Acc	1b	1b
Acc	4a	4a	PMm, Plpg	1d	1d
PMm, Plpm	3b	3b	Plpm, Plpg	1c	1c
PMm	2g	2g	Acc	2e	2e
PMm	3d	3d	Acc	2d	2d
PMm	3c	3c	Acc, PMm	2c	2c
PMm	3a	3a	Acc	2b	2b
PMm	1h	1h	Acc	2a	2a
PMm	1g	1g	Acc	1a	1a

STUDY AREA

- ▲ GOLD DEPOSIT (PLACER)
- GOLD DEPOSIT (HYDROTHERMAL)

FAULTS

MAP UNITS BOUNDARIES

UTM CORNER COORDINATES

A 409000E 9365000N

B 475000E 9309000N

**SAR-SIPAM
TAPAJÓS
AREA IRIRI**

L-HH

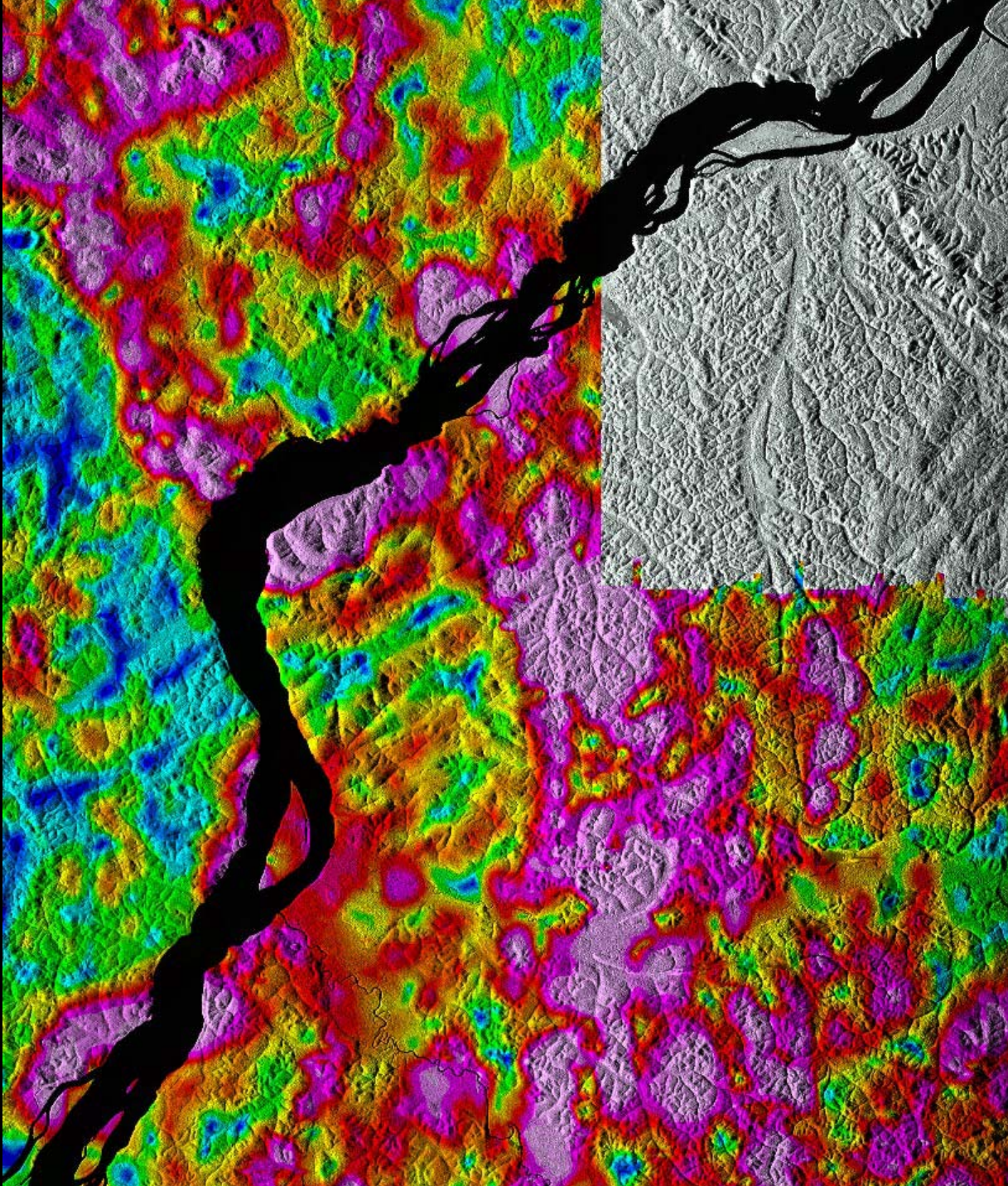
L-HV

6m

AREA IRIRI

**T.A. Carrino
W. Paradella**





**SAR-SIPAM
TAPAJÓS
AREA IRIRI**

L-HH

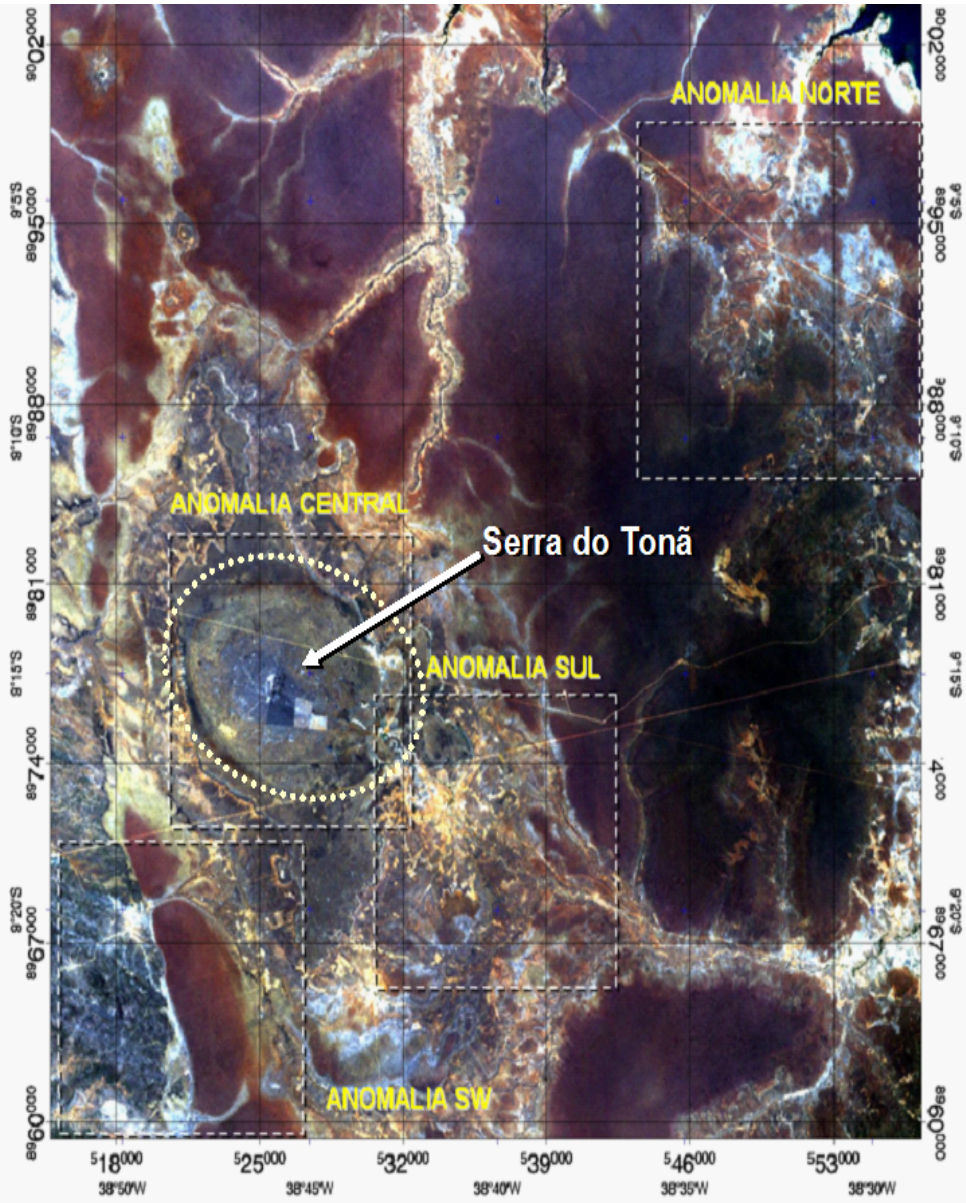
L-HV

6m

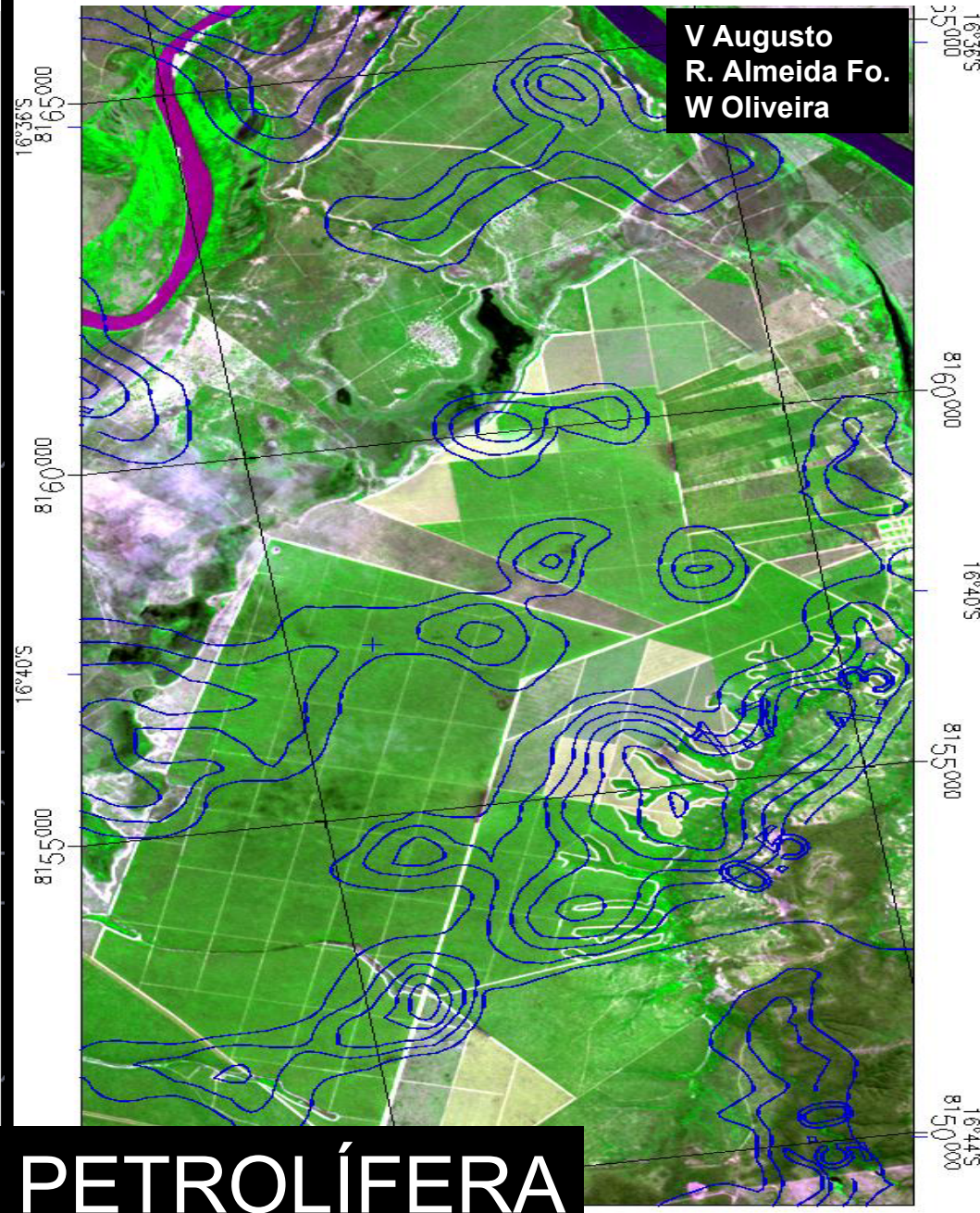
AREA IRIRI

**T.A. Carrino
W. Paradella**

(HCs)



Bacia São Francisco (HCs)

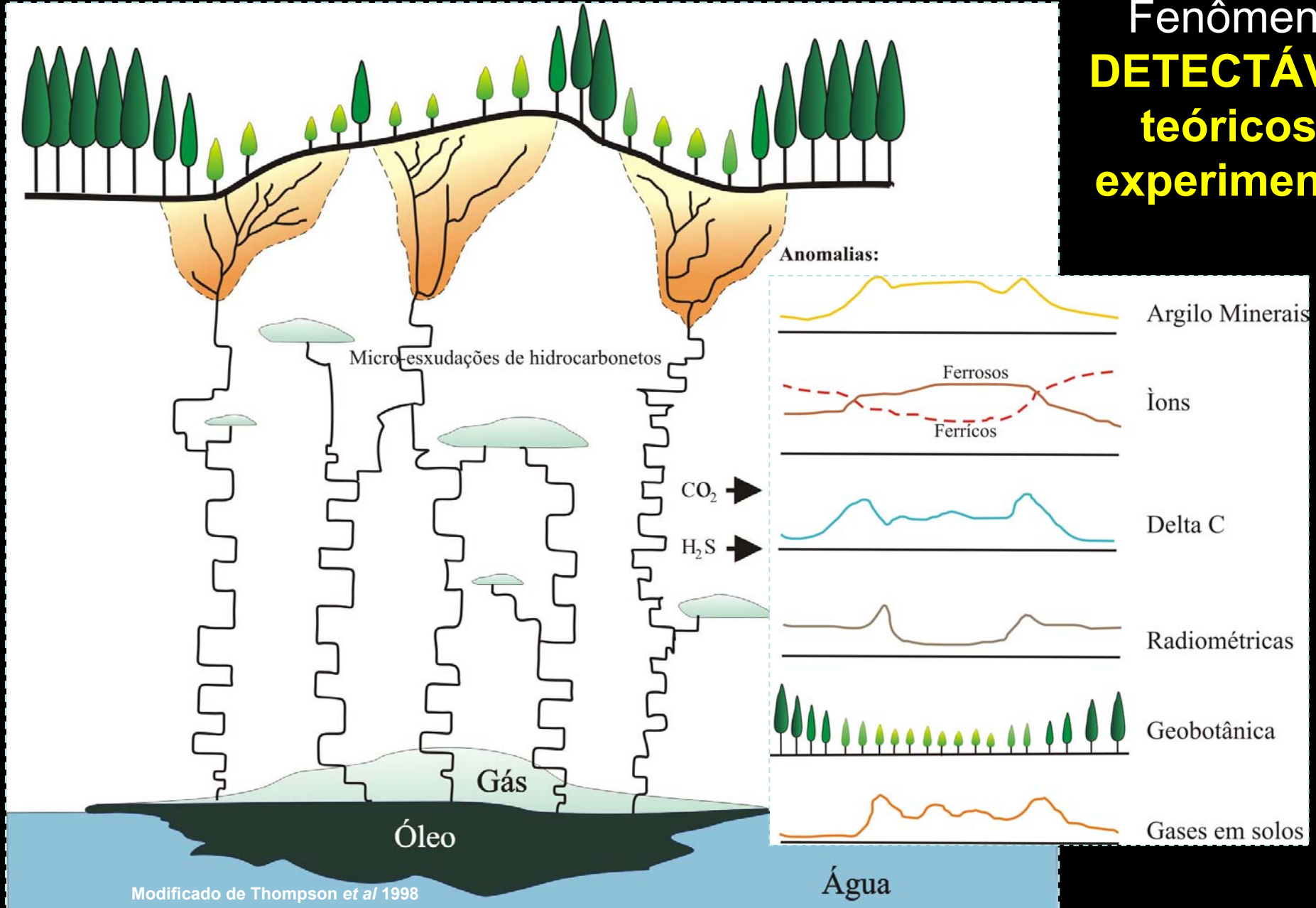


Land sat ET M+ (ponto/órbita 216/66)
30 de setembro de 1999
Composição colorida: bandas 321 (RGB)



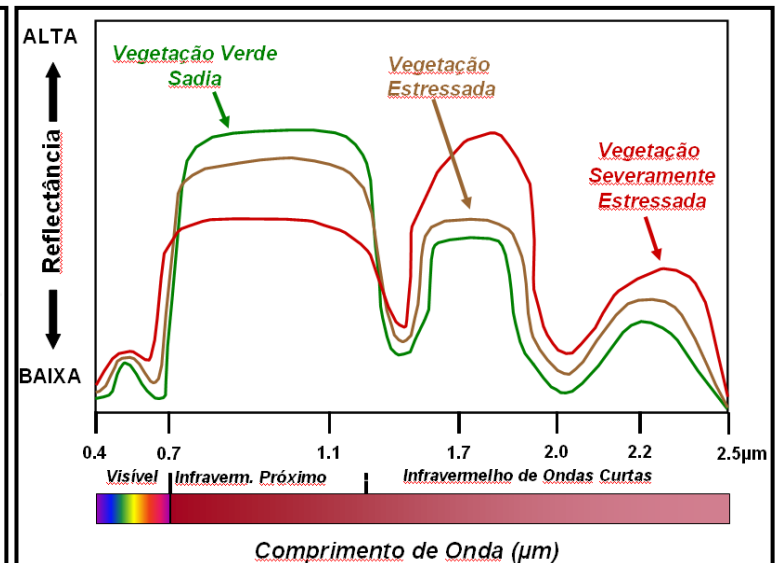
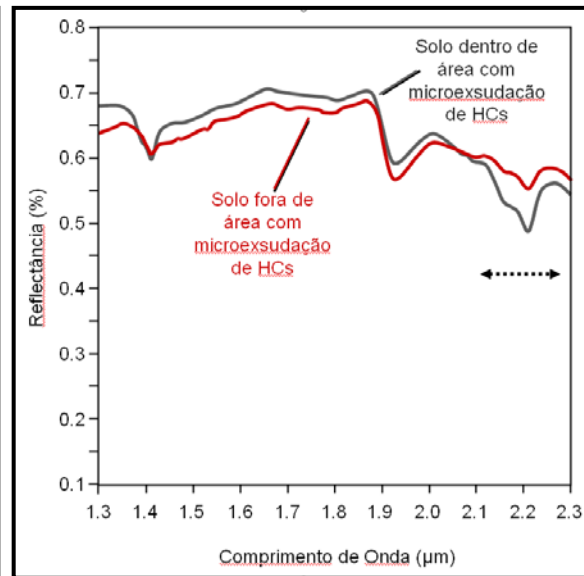
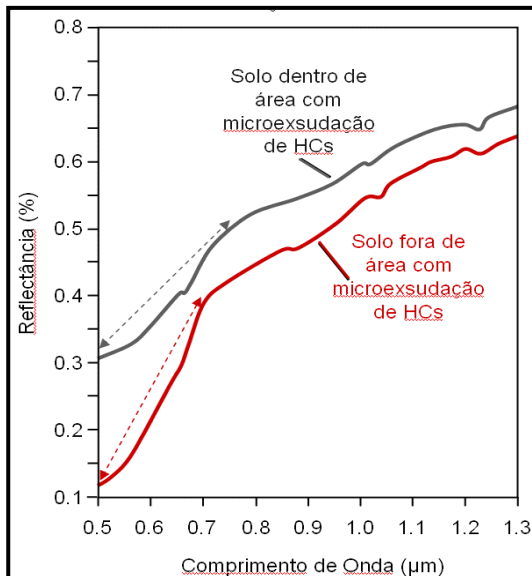
EXPLORAÇÃO PETROLÍFERA

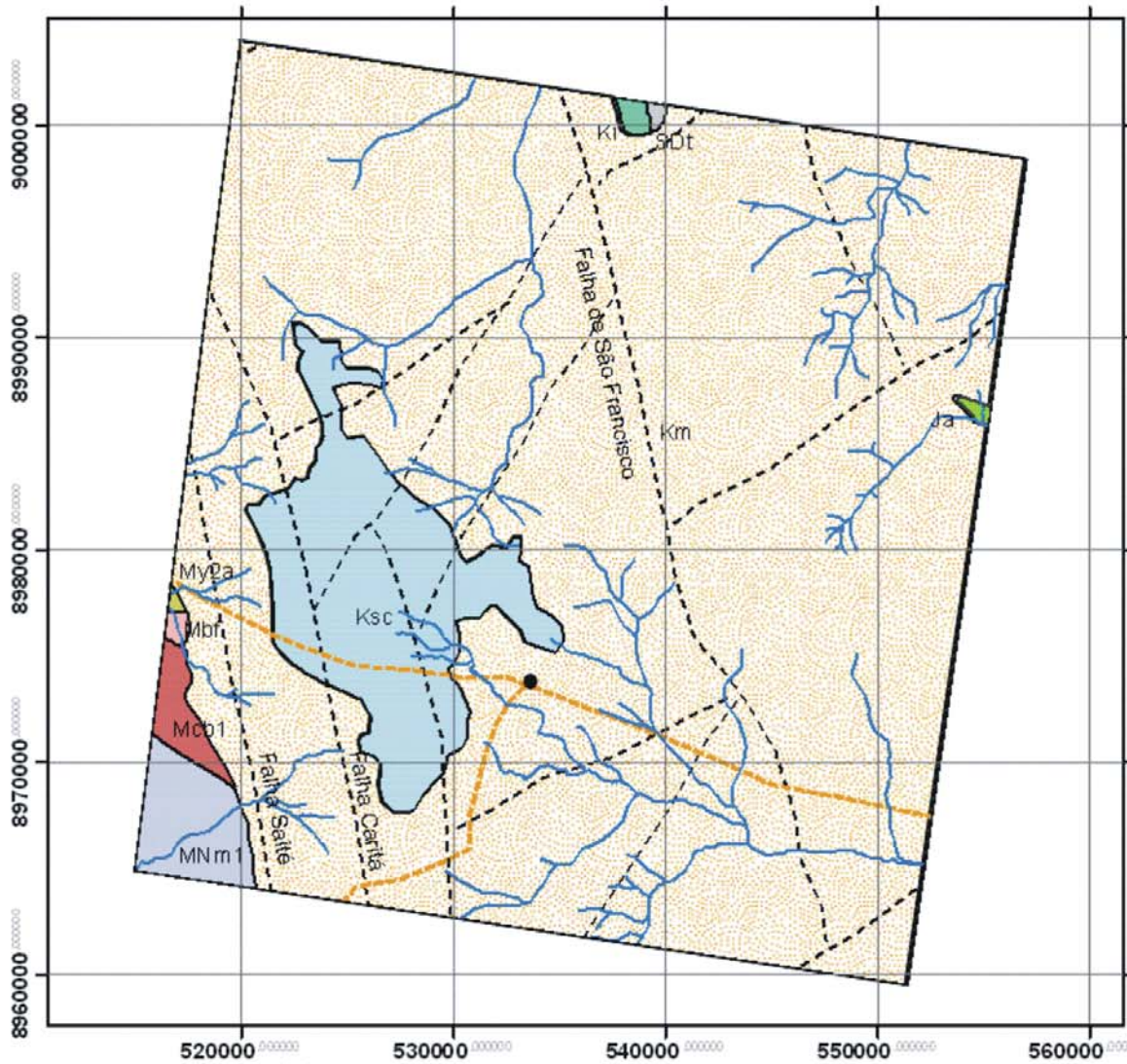
Fenômenos **DETECTÁVEIS** teóricos e experimentais



Modelo Teórico-Experimental

Feição/Fenômeno	Modo de detecção
Bleaching - remoção de íon férrico (hematita, goetita e minerais limoníticos) por soluções ácidas/redutoras	Mudança do comportamento espectral no visível (perda do Fe – férrico) Presença de minerais Fe-ferroso (VNIR)
Argilo-Minerais (caulinita/ilita) – soluções ácidas/redutoras promovem alterações diagenéticas de feldspatos	Feições espectrais da caulinita (<i>doublet</i> de absorção – 2,16 e 2,2 μm)
Vegetação – sensível à toxidez do solo por hidrocarbonetos e compostos associados	Deslocamento do ponto de inflexão do ‘red edge’ (<i>‘red shift’</i> e <i>‘blue shift’</i>)





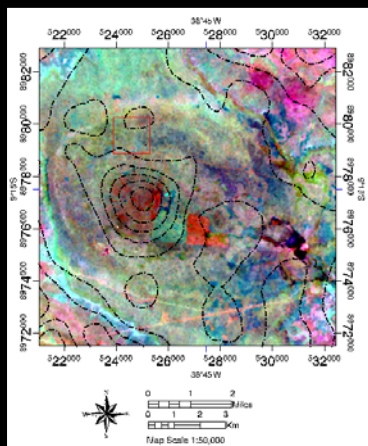
Bacia do Tucano



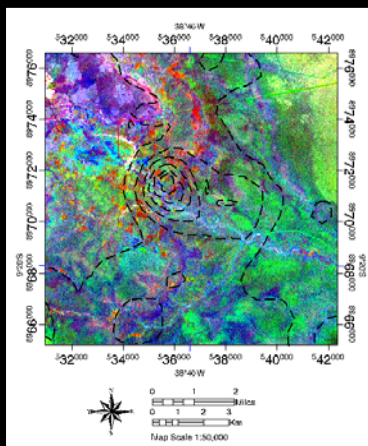
Legenda

- Localidades
 - Rios
 - Estradas
 - - - Falhas/Fraturas
- Unidades Geológicas**
- Mesozóico**
- Formação Santana ou Sequência do Toná (Ksc)
 - Formação Ipirital (Km)
 - Grupo Ilhas (Ki)
- Mesoproterozóico a/ou Neoproterozóico**
- Suítas magnéticas (My2a)
 - Grupo Macururê (MNm1)
 - Complexo Cabrobó (Mb1)
 - Complexo Belém do São Francisco (MBF)
- Paleozóico**
- Grupo Jatobá**
- Formação Tacaratu (SDt)
- Grupo Brotas**
- Formação Aliança (Ja)
- Terciário**
- Pós-Rift
 - Sin-Rift
 - Pré-Rift
 - Paleozóico
 - Embasamento

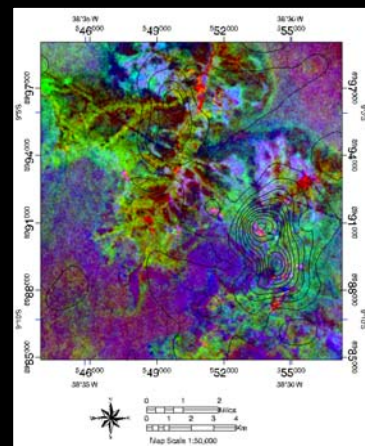
Anomalia Central



Anomalia Sul

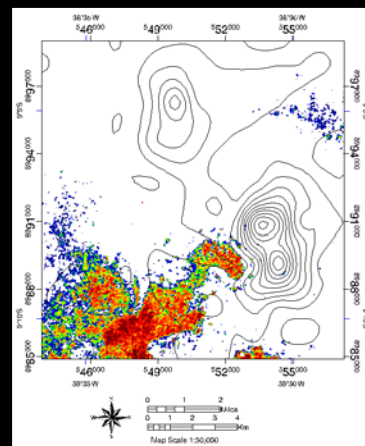
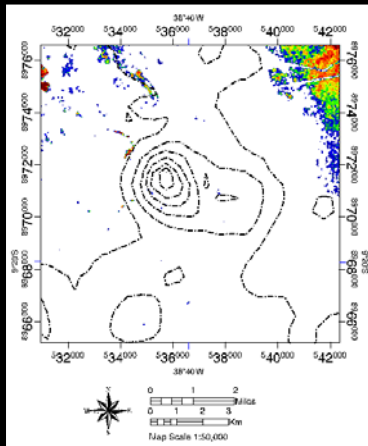
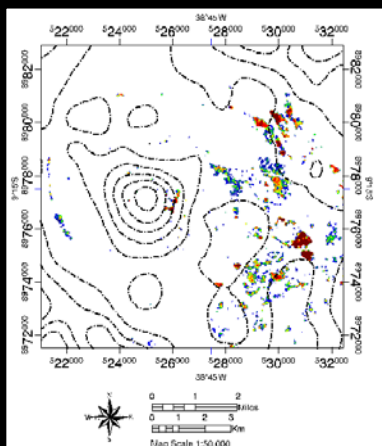


Anomalia Norte



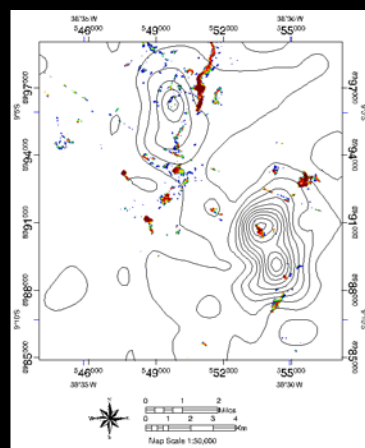
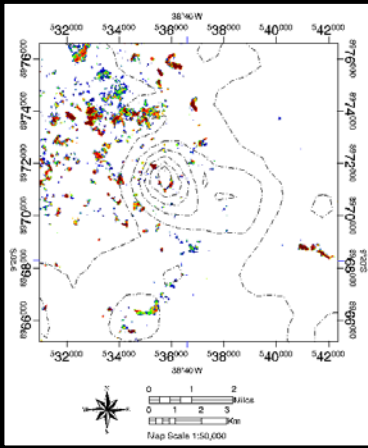
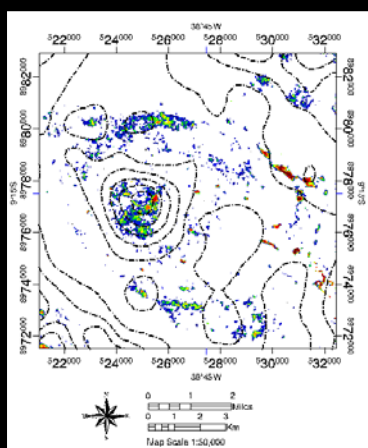
- (R) Fe-ferroso
- (G) Fe-férrico (goethita)
- (B) Fe-férrico (hematita)

Abundância de
vegetação
fotossinteticamente
ativa



Dados:
TM/Landsat
Processamento
pseudo-razões

Imagem de
abundância de
argilas e/ou
carbonatos

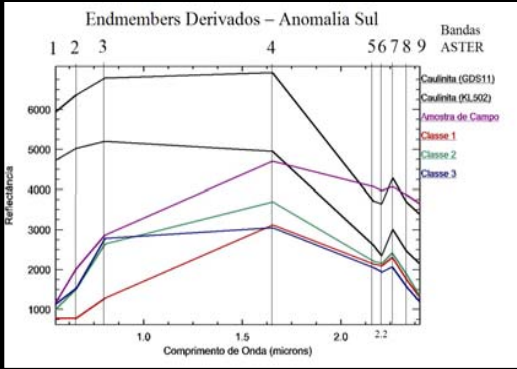


Anomalia SUL

SAM

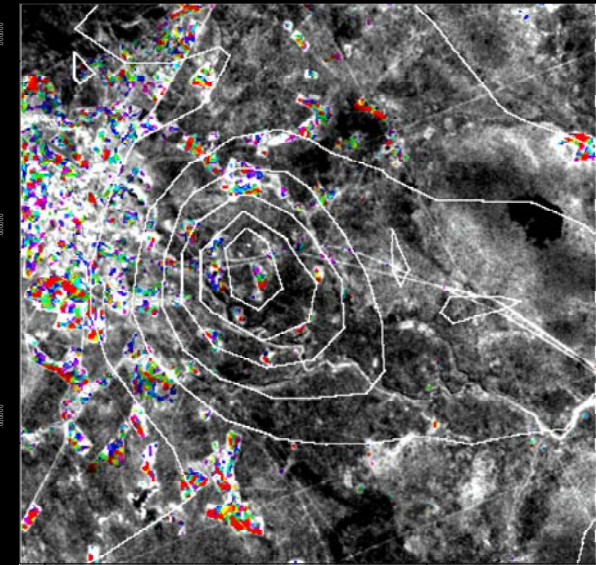
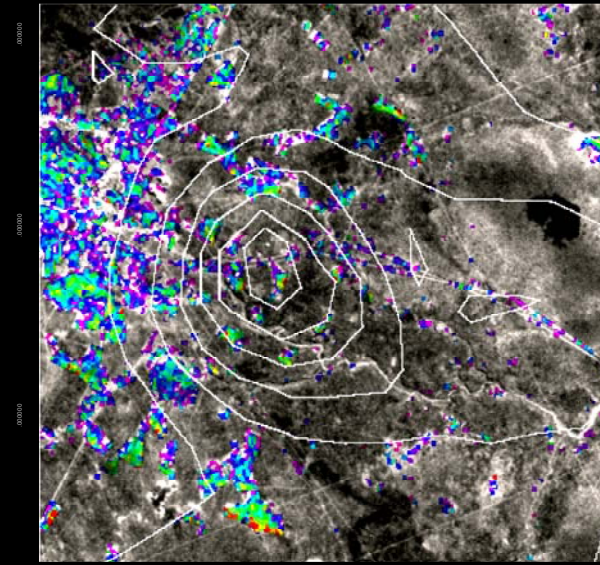
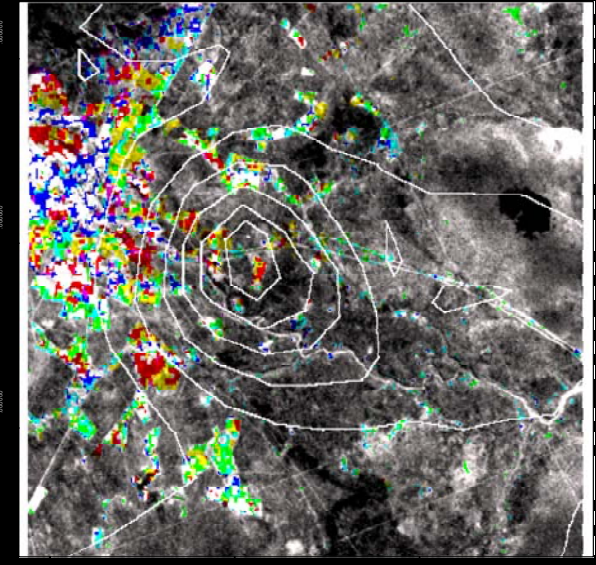
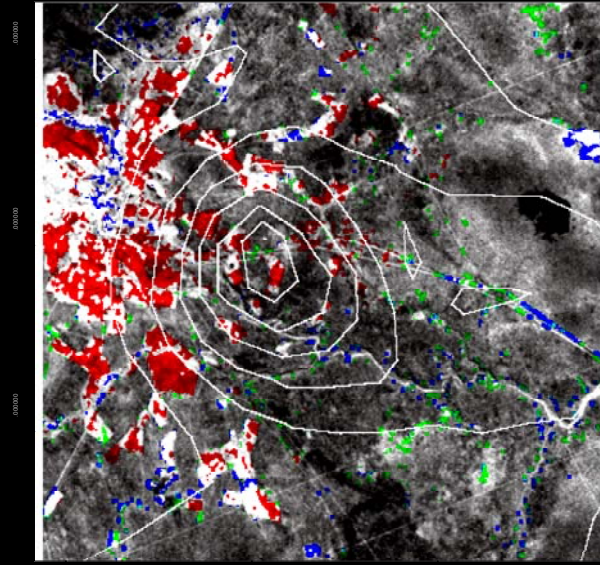
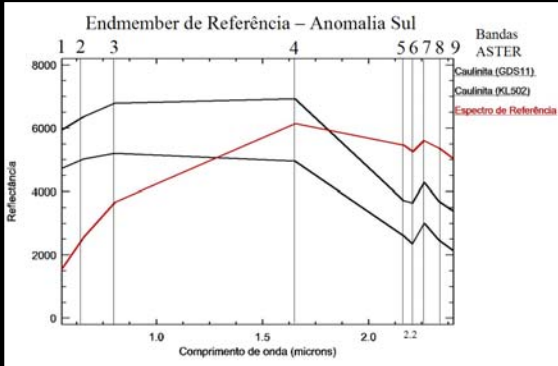
MTMF

Espectros Utilizados

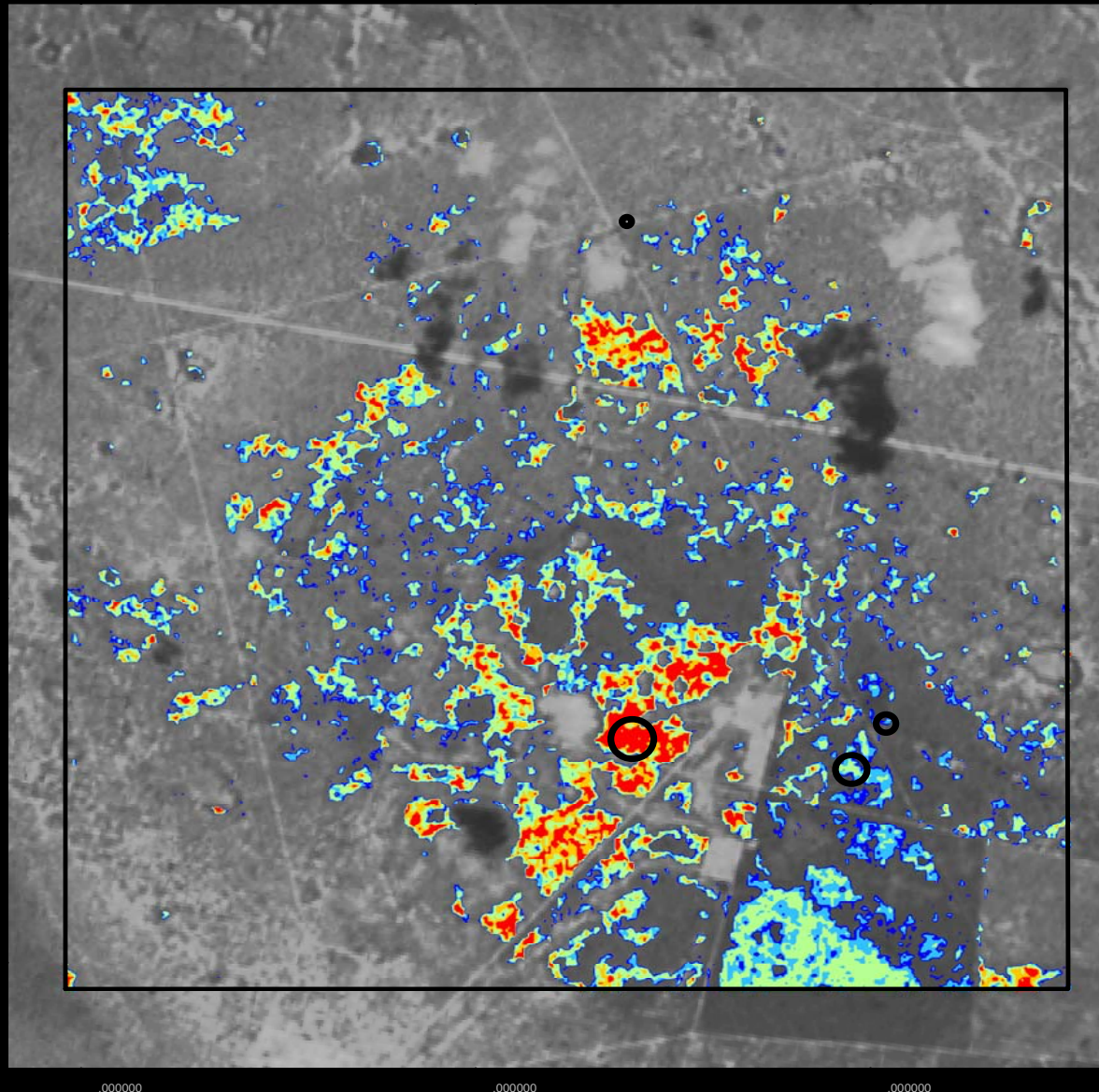


Dados: ASTER

Processamento hiperespectral



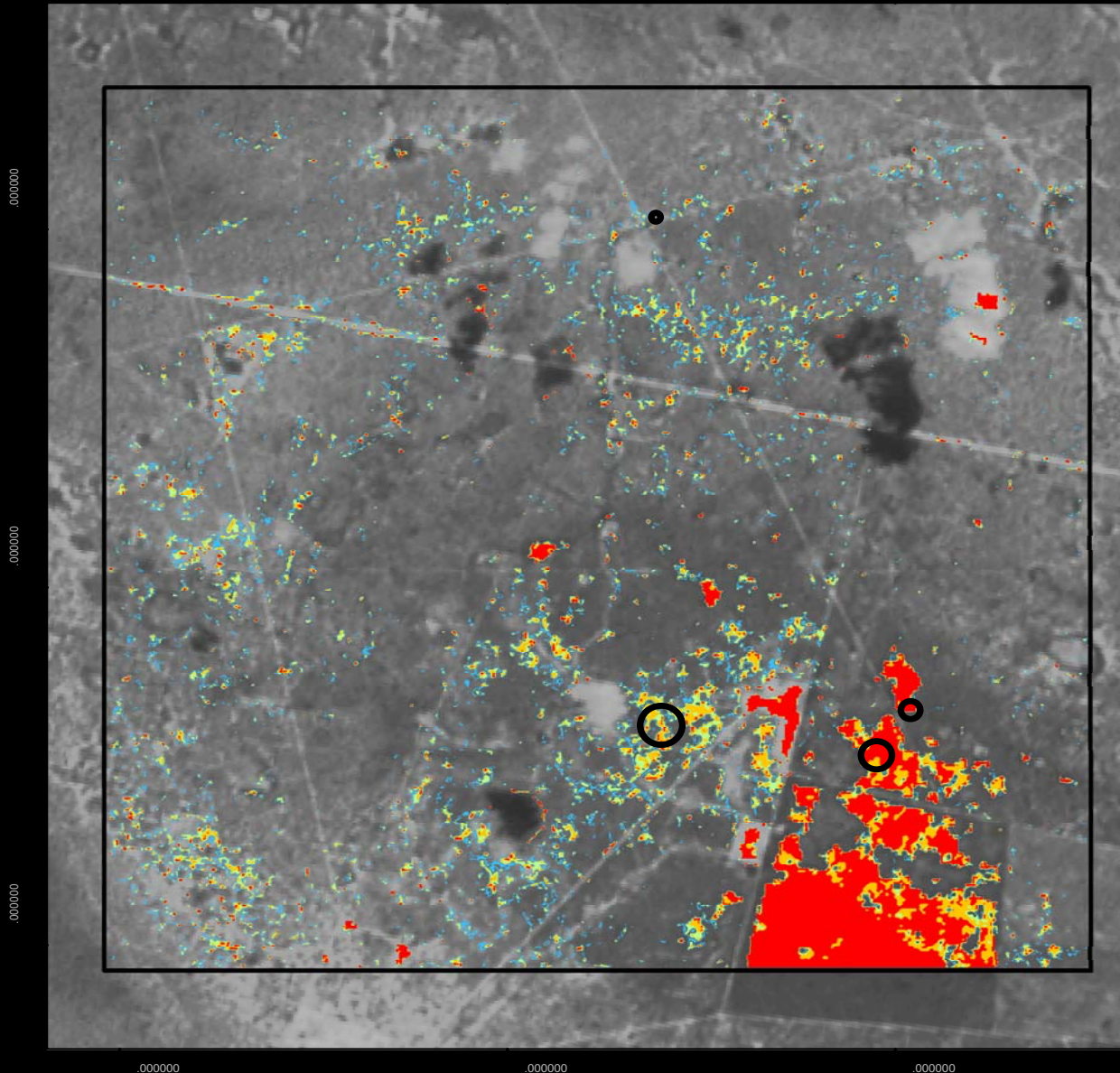
Anomalia Central - PNN



Dados:
ASTER

Processamento
NNts
(Probabilistic
Neural Network)

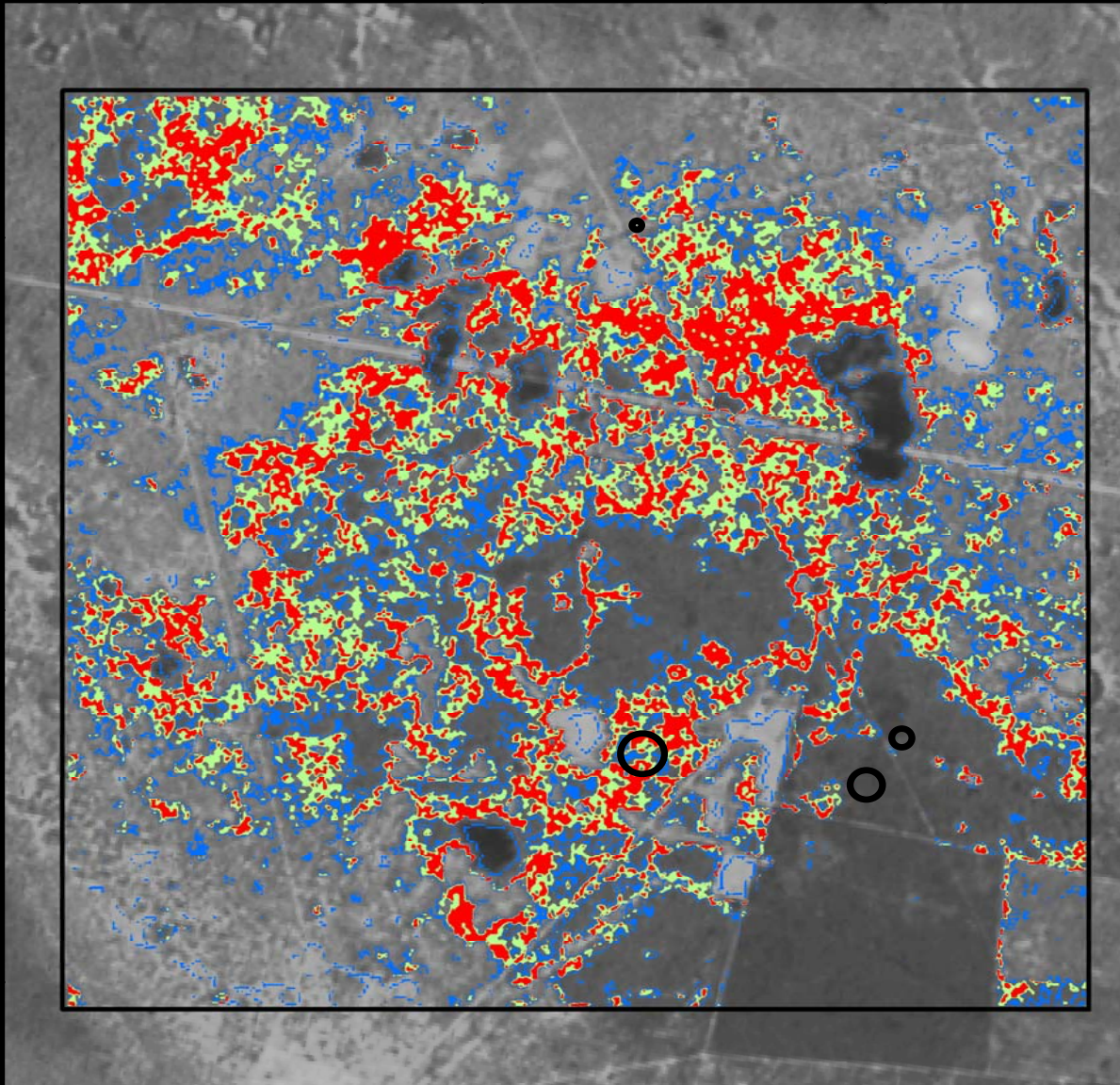
Área Central - RBFLN



Dados:
ASTER

Processamento
NNts
(Radial Basis
Functional Link
Network)

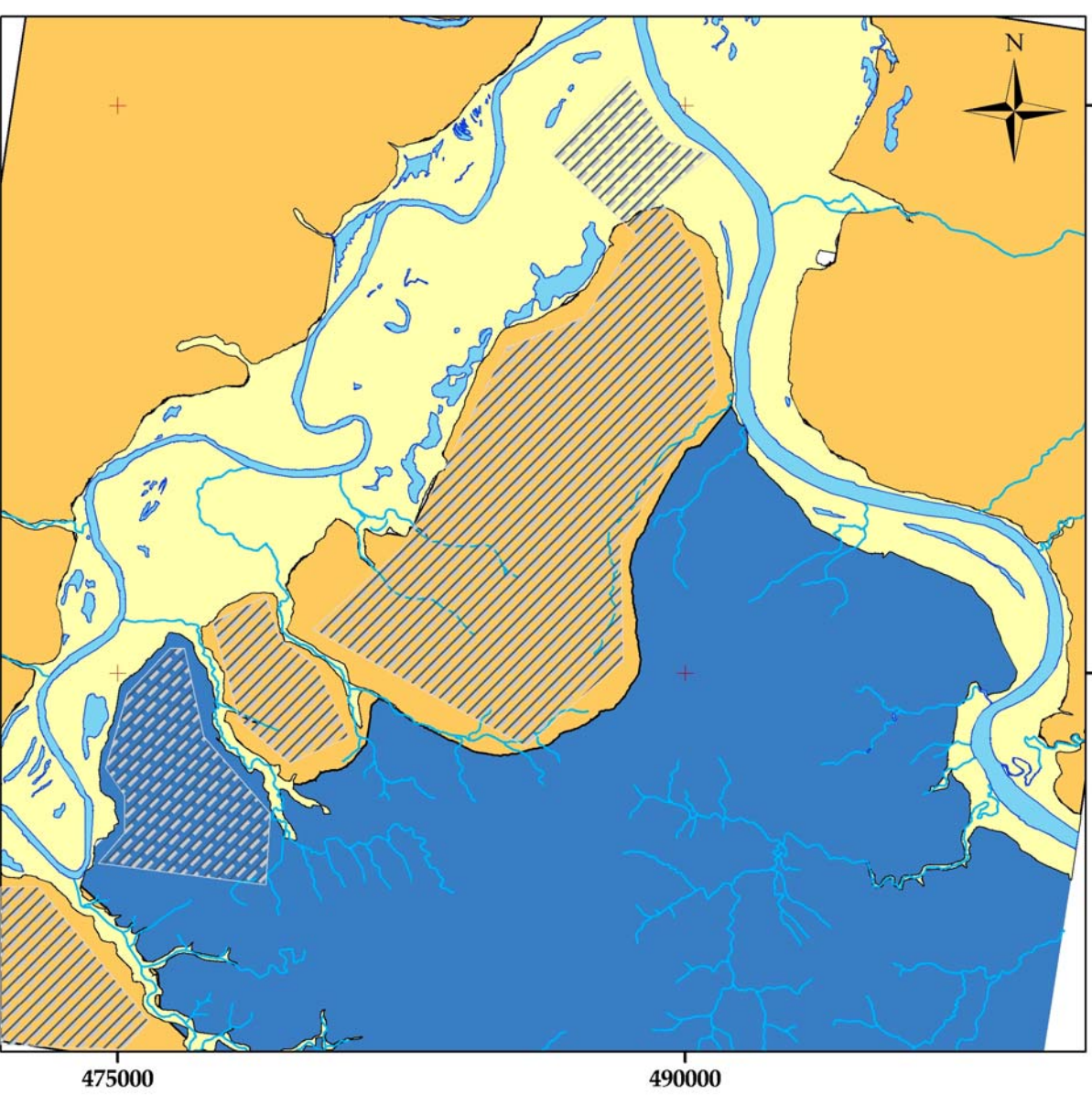
Anomalia Central – Fuzzy Clustering




Dados:
ASTER

Processamento
NNts
(Fuzzy
Clustering)

Bacia São Francisco



Legenda

-  Grupo Bambuí
-  Cobertura elúvio-coluvionares areno-argilas
-  Cultura de eucaliptos
-  Depósitos fluviais arenosos, com lentes de silte, argilas e cascalhos
-  Drenagem





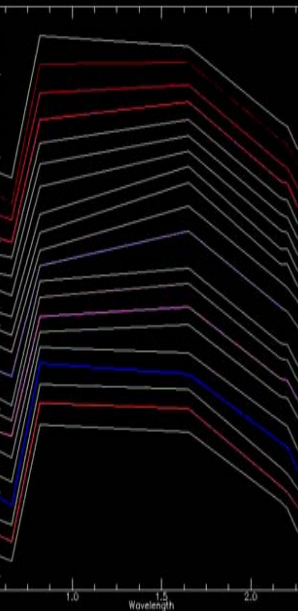
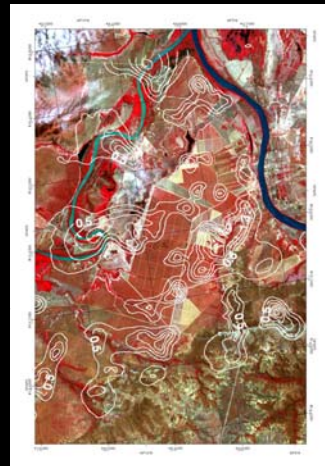
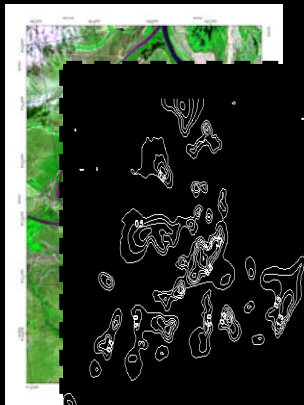
Síntese Metodológica

Caracterização espectral

Dados Geoquímicos

Imagem ASTER

Integração



Área alvo

Análise espectral

Espectro característico

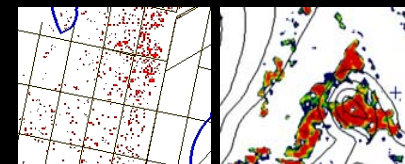


Mapeamento Espectral

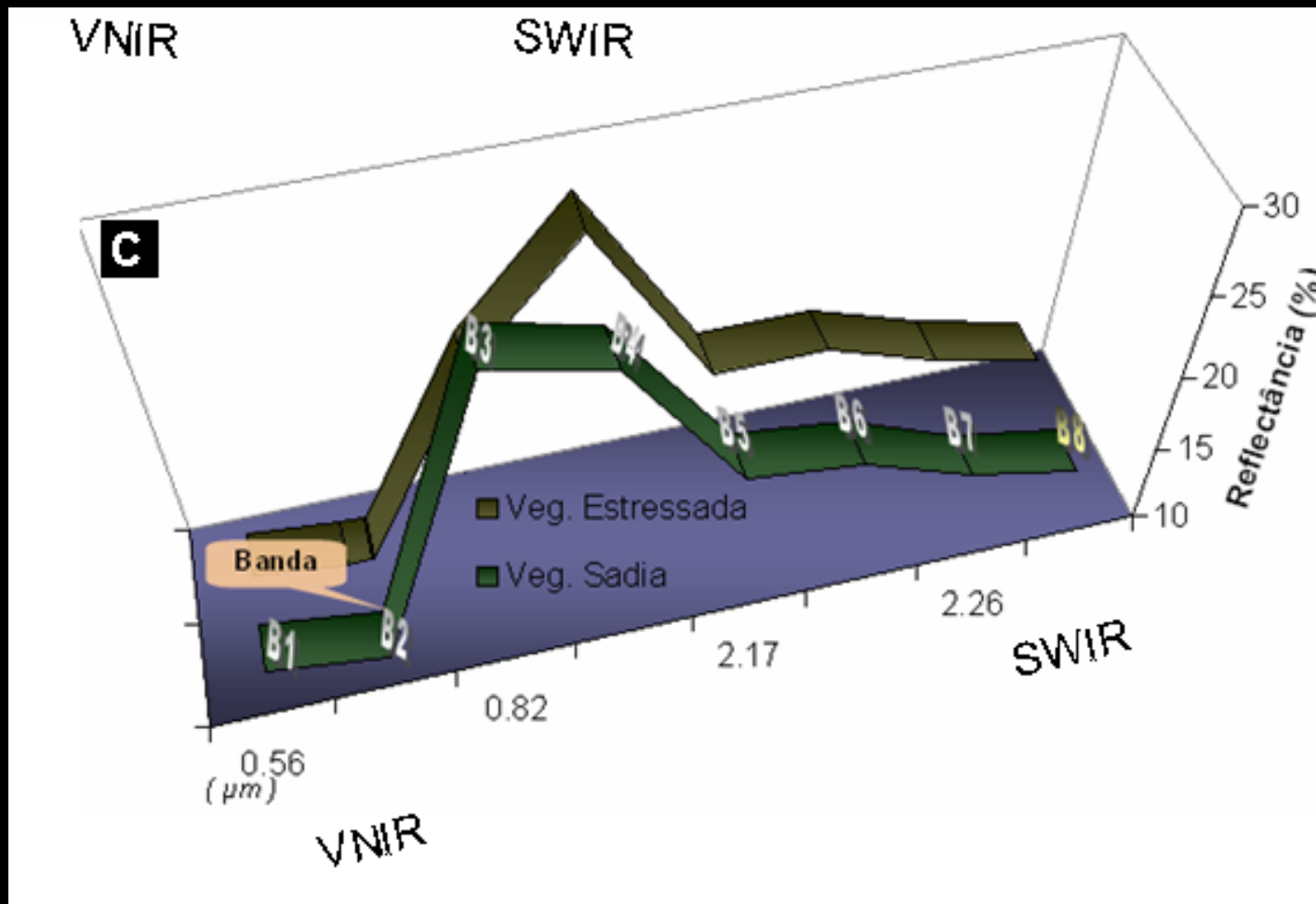
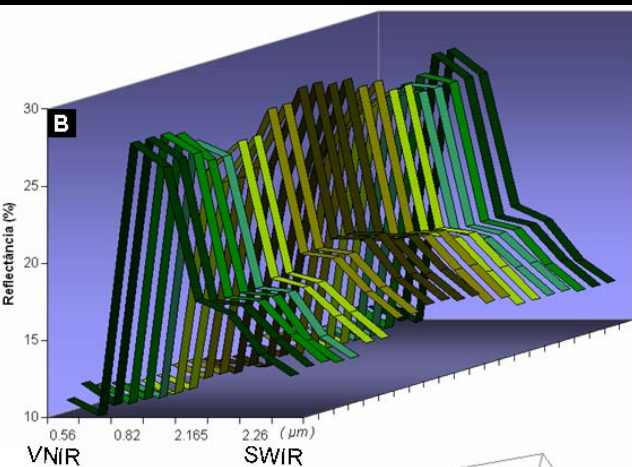
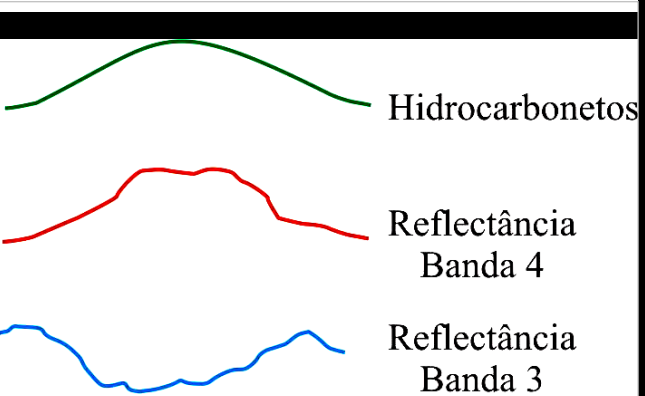
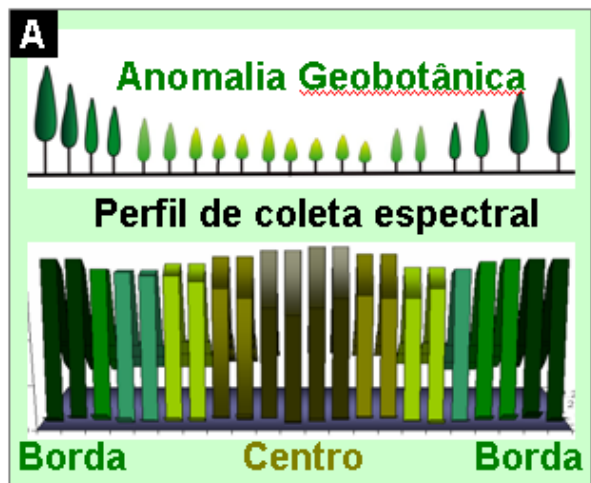
MTMF

SAM

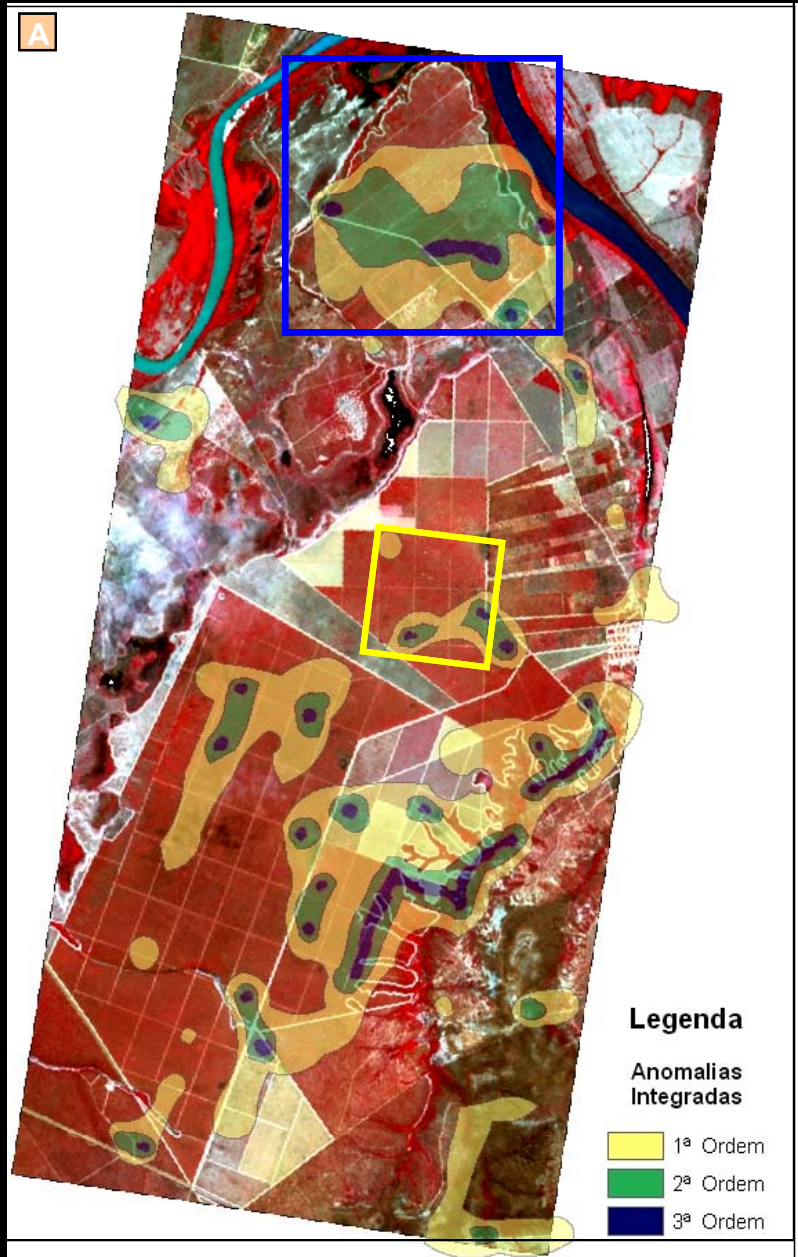
Vegetação Estressada



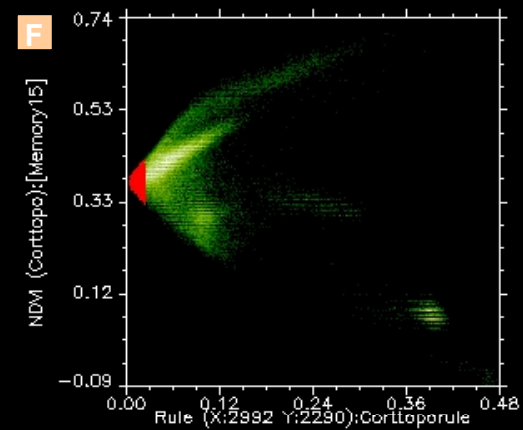
ESPECTRO CARACTERÍSTICO



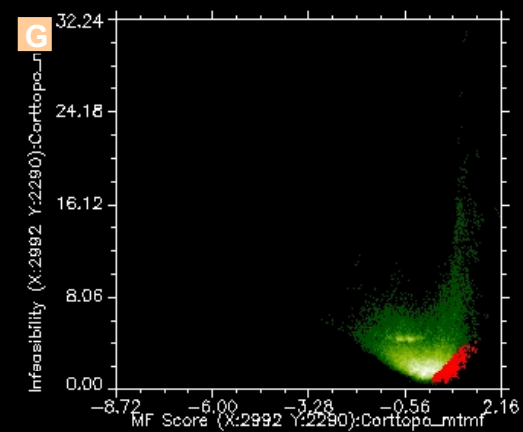
Período de estiagem



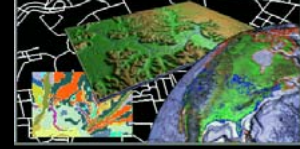
SAM + NDVI



MTMF



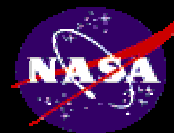
CONSIDERAÇÕES FINAIS



- **Imagens e métodos** para geração de dados terrestres de **sensoriamento remoto** encontram-se amplamente disponíveis para a comunidade, em geral, gratuitamente ou a custos simbólicos.
- **Algoritmos e software** para processamento de imagens e análise espacial de dados também existem em versões sem custos (SPRING, ArcSDM, etc).
- **Casos de sucesso** no uso dessas **Geotecnologias** em exploração mineral e petrolífera dependem essencialmente de um **bom modelo de detecção**
- **SOLUCÕES SR = boas IDÉIAS !**



Obrigado!



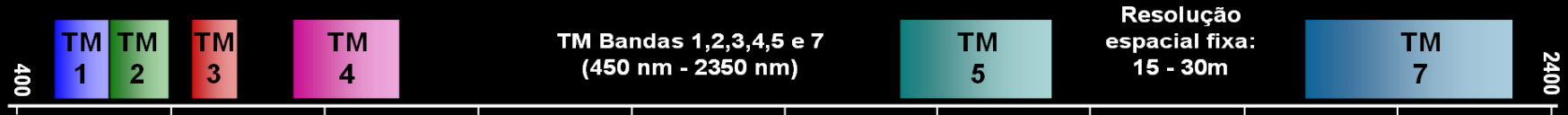
Instituto de Geociências
Universidade Estadual de
Campinas (UNICAMP)

www.ige.unicamp.br

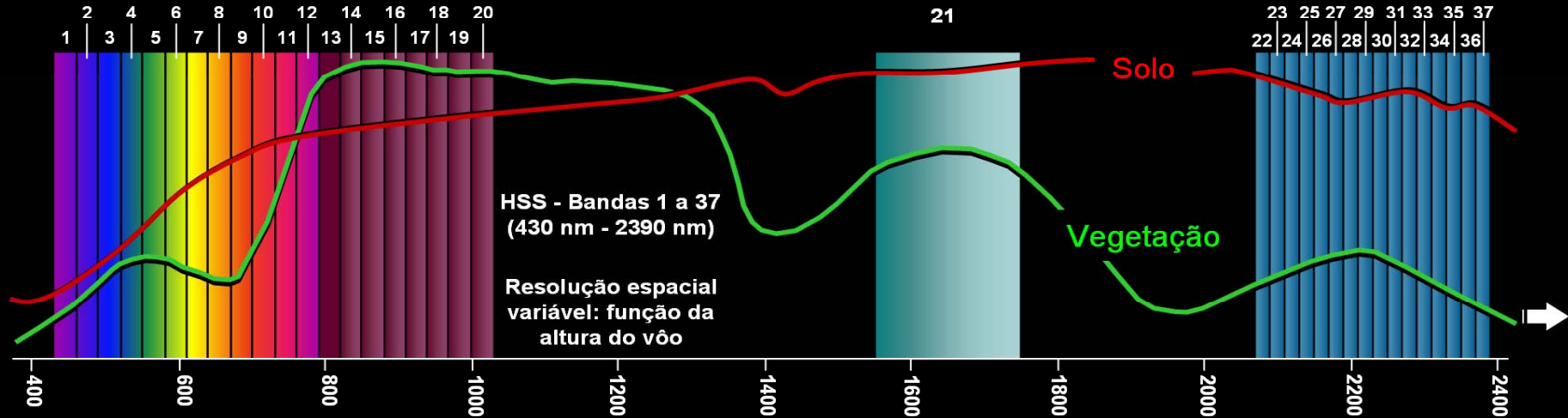
beto@ige.unicamp.br



Sensores Multiespectrais TM & ETM+ / Landsat - 5 & 7



Sensor Hiperespectral HSS / R98 (SIVAM)



← VIS →
← InfraV. Próximo (NIR) →
← InfraV. de Ondas Curtas (SWIR) →

