



Universidade de Brasília
Instituto de Geociências
Programa de Pós-graduação em Geologia

CONTROLES DA MINERALIZAÇÃO DE OURO E ARQUITETURA DO SISTEMA MINERALIZANTE NO COMPLEXO MINEIRO JACOBINA (BA)

CONTROLS ON THE GOLD MINERALIZATION AND
ARCHITECTURE OF THE MINERALIZING SYSTEM AT
THE JACOBINA MINING COMPLEX (BA)

GABRIEL DA SILVA SEIDLER

Dissertação de mestrado N° 524

Orientadora: Prof.^a. Dra. Catarina L. B. Toledo

Coorientador: Prof. Dr. Farid Chemale Jr.

Brasília, 27/03/2024



Universidade de Brasília

Instituto de Geociências

Programa de Pós-graduação em Geologia

CONTROLES DA MINERALIZAÇÃO DE OURO E ARQUITETURA DO SISTEMA MINERALIZANTE NO COMPLEXO MINEIRO JACOBINA (BA)

**CONTROLS ON THE GOLD MINERALIZATION AND
ARCHITECTURE OF THE MINERALIZING SYSTEM AT
THE JACOBINA MINING COMPLEX (BA)**

GABRIEL DA SILVA SEIDLER

Dissertação apresentada ao
Programa de Pós-Graduação
em Geologia – Instituto de
Geociências – IG da
Universidade de Brasília – UnB
como requisito parcial
obrigatório para a obtenção do
título de Mestre em Geologia.

Área de concentração:
Geologia Econômica e
Prospecção

Orientador: Prof. Dra. Catarina
L. B. Toledo

Comissão Examinadora:

Prof. Dra. Catarina Labouré Bemfica Toledo (UnB);

Prof. Dr. Fernando César Alves da Silva (externo);

Prof. Dr. Claudinei Gouveia de Oliveira (UnB);

Prof. Dr. Luis Gustavo Ferreira Viegas (Suplente IG/UnB).

dS458DA
SILVAC

da Silva Seidler, Gabriel

CONTROLES DA MINERALIZAÇÃO DE OURO E ARQUITETURA DO
SISTEMA MINERALIZANTE NO COMPLEXO MINEIRO DE JACOBINA
(BA) /

Gabriel da Silva Seidler; orientador Catarina Labouré
Bemfica Toledo; co-orientador Farid Chemale Júnior. --
Brasília, 2024.

79 p.

Dissertação (Mestrado em Geologia) -- Universidade de
Brasília, 2024.

1. Sistemas minerais. 2. corredores de alto teor de ouro.
3. Modelagem 3D. 4. Microtomografia Computadorizada de
 Raios-X. 5. Distrito Mineiro de Jacobina . I. Labouré
Bemfica Toledo, Catarina, orient. II. Chemale Júnior, Farid,
co-orient. III. Título.

Agradecimentos

Começo agradecendo ao meu altar feminino: à minha mãe, Nilva, que me deu a vida, e que durante toda a sua vida, me incentivou, motivou, apoiou e guiou incondicionalmente. Agradeço, também, as minhas outras mães, minha avó Maria Antônio, que me orienta em pensamento, e minha irmã Caroline, pelo amor e apoio por toda a vida. À minha mãe Iansã e madrinha Yemanjá, que me acompanham desde o nascimento. À minha orientadora-mãe, Catarina, e a minha coorientadora-mãe do coração, Adalene, pela paciência e ajuda nesse caminho.

Agradeço à Cal pelos exemplos de ética e educação, ao meu pai, Gilnei, pelos ensinamentos a distância. Ao meu coorientador, Professor Farid, pelas aulas e ensinamentos valorosos. Ao meu pai Oxóssi e ao meu guia Ogum, que me orientam, me protegem, me dão caminho e perseverança.

À Bia, muito, muito obrigado. Nada disso aconteceria se não fosse você na minha vida. Aos trancos e barrancos, contra tudo e contra todos, conseguimos! Obrigado pelo apoio, pelas broncas, pelos afagos nas dificuldades, e por fazer parte do meu dia a dia. A gente sabe, e sabe bem.

Agradeço especialmente aos amigos que me aguentam e se mantêm firmes mesmo em meio as inúmeras reclamações: Jéssica, André, Rafa, Rodrigo, Leo, Ian, Itiel, Airton, Pimentel, Bruno, Gabriel Costa, Magno e Guido, dentre tantos outros que abrilhantam os ébrios momentos de alegria e música ao longo desses anos.

Aos meus amigos e colegas de exploração: Matheus, e sua paciência quase sempre presente, João, Michelli, Brenda, Paola, Dangola, Rodolfo, Cláudio, Robson, Gabriel Ito e seus questionamentos e provocações e, em especial, à Juliano José de Souza, que desde o início acreditou e apoiou meu trabalho.

Agradeço, por fim, a Jacobina Mineração e Comércio por disponibilizar a estrutura e o financiamento para este trabalho, e a professora Adriana Chatack e Renato, do Laboratório de Propriedades Físicas das Rochas da UnB, pelo apoio nas análises de Micro-CT. O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil (CAPES) – Código de Financiamento 001.

“Empty your mind. Be formless, shapeless, like water.

You put water into a cup, it becomes the cup. You put water into a teapot, it becomes the teapot. Water can flow, or it can crash.

Be water, my friend.”

Bruce Lee

Resumo

O Distrito Mineiro de Jacobina representa um importante depósito de Ouro associado a metaconglomerados, destacando-se por seu prolongado histórico de extração e grande potencial. Neste contexto, reconhecer os controles dos corredores de alto teor é fundamental para atividades de exploração mineral e lavra.

Neste trabalho foram identificados os parâmetros críticos envolvidos na formação dos corredores de alto teor do Distrito Mineiro de Jacobina, visando compreender a arquitetura do sistema mineralizante e gerar vetores prospectivos para a exploração de ouro na região. Para tal, foram realizados mapeamentos litoestruturais em superfície e em galerias de minas subterrâneas, seguido por modelagem tridimensional dos corpos mineralizados, utilizando projeções de máxima intensidade, interpolações por Função de Base Radial e de teor de ouro *versus* espessura dos *ore shoots* para o reconhecimento da geometria dos corpos mineralizados. Adicionalmente, foram realizadas descrições de testemunhos de sondagem, análises petrográficas e aplicação de Microtomografia Computadorizada de Raios-X (Micro-CT), para estudo das características texturais e mineralógicas das zonas de alto teor.

Foram identificados quatro eventos deformacionais significativos, responsáveis pela construção do arcabouço estrutural e pela conformação da arquitetura e geométrica do sistema mineral de Jacobina. A análise dos padrões da mineralização nas minas do distrito, permitiu sua individualização em três domínios estruturais, denominados Domínio Norte, Domínio Central e Domínio Sul. A associação das observações de campo com os produtos oriundos das técnicas de modelagem tridimensional e a Micro-CT, permitiram a compreensão dos controles atuantes sobre os caminhos pelos quais circularam os fluidos que remobilizaram o ouro e, sobretudo, elucidaram os fatores controladores de sua acumulação e consequente concentração de ouro em zonas de alto teor, de forma que estruturas de primeira ordem, de direções predominantemente N-S, geradas durante os eventos compressivo e transpressivo, atuaram como condutos para fluidos mineralizantes, promovendo a circulação destes fluidos através das rochas encaixantes da mineralização, em todo o Distrito Mineiro de Jacobina. Por sua vez, estruturas de segunda ordem, dextrais, de direções E-W, geradas durante o evento transpressivo, antitéticas ao cisalhamento regional sinistral, desempenharam papel de barreiras de permeabilidade ou zonas de baixa pressão, promovendo a acumulação de fluidos mineralizados nas interseções destas com estruturas de primeira ordem,

culminando na formação regiões de alta concentração de ouro, ao longo de todos os domínios estruturais estudados. No Domínio Norte, estruturas antiformais, nucleadas durante o evento transpressivo, atuaram como importantes zonas de acumulação de fluidos, promovendo uma concentração do metal em zonas com teores de ouro significativamente maior do que nos demais domínios estruturais estudados.

Concluiu-se, por fim, que o estudo, em escala de depósito, dos fatores críticos do sistema mineralizante atuante no Distrito Mineiro de Jacobina (arquitetura, geodinâmica, fertilidade e preservação) permitiu, não só uma robusta compreensão da arquitetura e da geometria do sistema, mas também a definição dos parâmetros envolvidos na geração de corredores de alto teor, mostrando-se um eficiente caminho na busca pelo entendimento do prolífico, e único, Sistema Mineral de Jacobina.

Palavras-Chave: Sistemas minerais; corredores de alto teor de ouro; Modelagem 3D; Microtomografia Computadorizada de Raios-X; Distrito Mineiro de Jacobina

Abstract

The Jacobina Mining District represents an important gold deposit associated with metaconglomerates, notable for its extensive history of extraction and substantial potential. In this context, understanding the controls of high-grade shoots is crucial for mineral exploration and mining activities.

This study identified critical parameters influencing the formation of high-grade shoots in the Jacobina Mining District, aiming to comprehend the architecture of the mineralizing system and generate prospective vectors for gold exploration in the region. To achieve this, lithostructural mappings were conducted both at surface and in underground mine galleries. This was followed by three-dimensional modeling of mineralized bodies using maximum intensity projections, radial basis function interpolations, and gold grade versus ore shoot thickness relationships to recognize the geometry of mineralized bodies.

Additionally, drill core descriptions, petrographic analyses, and the application of X-ray Computed Microtomography (Micro-CT) were performed to study the textural and mineralogical characteristics of high-grade zones. Four significant deformational events were identified, contributing to the structural framework and shaping the architecture and geometry of the Jacobina mineral system.

Analysis of mineralization patterns in the district's mines allowed the delineation of three structural domains: North Domain, Central Domain, and South Domain. Integration of field observations with outputs from three-dimensional modeling techniques and Micro-CT facilitated understanding of the controlling factors governing the pathways through which gold-bearing fluids circulated and remobilized gold. Importantly, it elucidated factors responsible for gold accumulation in high-grade concentration zones.

First-order structures, predominantly N-S trending, formed during compressive and transpressive events, acted as conduits for mineralizing fluids, facilitating fluid circulation through host rocks across the Jacobina Mining District. Second-order dextral structures, oriented E-W and generated during the transpressive event as antithetic to sinistral regional shear, served as barriers or low-pressure zones, promoting accumulation of mineralized fluids at intersections with first-order structures. This culminated in the formation of high gold shoots across all studied structural domains. In the North Domain,

antiformal structures nucleated during the transpressive event played a significant role in fluid accumulation, resulting in significantly higher gold grades compared to other structural domains studied.

In conclusion, this deposit-scale study of critical factors of the mineralizing system in the Jacobina Mining District (architecture, geodynamics, fertility, and preservation) not only provided a robust understanding of the system's architecture and geometry but also defined parameters involved in generating high-grade ore shoots. This approach proved to be effective in enhancing understanding of the prolific and unique Jacobina Mineral System.

Key words: Mineral Systems; Gold high grade ore shoots; 3D Modelling; X-Ray Computed Microtomography; Jacobina Mine.

Lista de Figuras

Fig. 1. Mapa de localização do município de Jacobina.....	18
Fig. 2. Schematic sketch of the main geotectonic units present in the northern portion of the Contendas-Jacobina lineament. (Modified from Teles et al., 2017, Reis et al., 2021, dos Santos et al., 2019).....	30
Fig. 3. (a) Geological map of the Jacobina Range. (b) Stratigraphic column of the Jacobina Group. Modified from Teles et al., (2015), Pearson et al., (2005), and Mascarenhas et al., (1998).....	31
Fig. 4. Comparative stratigraphy of the mines in the Jacobina Mining District and the mineralized metaconglomerate bodies (Reefs) found in each of them. Reproduced from Soares et al., (2020). In the figure, only the bodies under active exploitation are represented in red. Exploratory targets or bodies with unmined mineralization are not depicted.....	32
Fig. 5. (a) Geological map of the Jacobina Mining District and location of its mines. (b) Schematic section showing the stratigraphy and geometry of the units constituting the Serra do Córrego Formation in the Canavieiras and Serra do Córrego mines. (c) Schematic section showing the stratigraphy and geometry of the units constituting the Serra do Córrego Formation in the João Belo mine.....	35
Fig. 6. (a) Stereogram of the poles of sedimentary bedding (S0); (b) Stereogram of the poles of foliation S1; (c) Stereogram showing the attitude of thrust faults F1; (d) Stereogram of the poles of foliation S2; (e) Stereogram of representative frontal ramp thrust faults F2a dipping to the North; (f) Stereograms of normal faults nucleated under extensional tectonics.....	41
Fig. 7. (a) Sedimentary bedding marked by intercalations of metaconglomerate and quartzite levels (S0 = 068°/64°) in outcrop of the Serra do Córrego Formation, in the João Belo region; (b) Growth fault F0 (06°/88°) in metaconglomerates of the Serra do Córrego Formation, mapped in a mining area in the João Belo region.....	42
Fig. 8. (a) S0//S1 displaying asymmetric folds with approximately N-S axes, in development face of the underground mine of Canavieiras Sul; (b) S1 foliation displaying asymmetric fold with approximately N-S axis (b1 = 354°/12°) in outcrop of the Serra do Córrego Formation; (c) S1 foliation exhibiting closed folds with sub-parallel limbs and approximately N-S axis (178°/30°); (d) F2 fault with approximately N-S direction (265°/75°) and well-defined sub-horizontal slickensides (Le2= 355°/04°), with steps indicating dextral kinematics; (e) Quartzite outcrop showing S-C foliation indicating left lateral movement.....	45
Fig. 09. Map representation of the northern, central, and southern structural domains of the Jacobina Mining District with stereographic diagrams of the main foliation and faults in the different domains.....	47
Fig. 10. (a) Maximum intensity projection of the interval midpoints described, in drillholes, as metaconglomerates, in the mines of the Northern Domain, with an orthogonal view to the dip of the layers. (viewed towards W, plunge -30°); (b) Representative disks of Sn foliation measurements obtained in systematic mapping of galleries in Canavieiras Sul mine showing their dip azimuth; (c) Stereogram of Sn foliations collected in development fronts in the underground mines of Canavieiras Sul, Canavieiras Central, and Canavieiras Norte with segregation of poles by quadrant. (d) Three-dimensional modeling of Sn foliations obtained in systematic mapping of galleries in Canavieiras Sul, Canavieiras Central, and Canavieiras Norte mines. Disks represent dip measurements of the foliations (viewed towards W, plunge +30°).....	48
Fig. 11. (a) Maximum intensity projection of the interval midpoints described as metaconglomerates in drillholes, in the mines of the Central Domain, with an orthogonal view to the dip of the layers. (viewed towards W, plunge -65°); (b) Representative disks of the direction measurements of foliations Sn obtained in systematic mapping of galleries in Morro do Vento and Morro do Cuscuz mines, showing their dip azimuth (Viewed towards W); (c) Representative disks of dip measurements of foliations obtained in	

systematic mapping of galleries in Morro do Vento Sul and Morro do Cuscuz mines (Viewed towards W).....49

Fig. 12. (a) Maximum intensity projection of the interval midpoints described as metaconglomerates in drillholes, in the Southern Domain, with a view perpendicular to the dip of the layers (viewed towards N); (b) Representative disks of the dip measurements of foliations S_n obtained in systematic mapping of galleries in João Belo Norte mine (viewed towards N); (c) Section of the geological-structural model of João Belo Norte mine (Viewed towards N) showing layer duplication and modelled shear zones.....50

Fig. 13. (a) Three-dimensional visualization, in plan view, depicting the interplay between high-grade interpolations derived from Radial Basis Function analysis of channel samples and the structural features of F2 and F2b in the LMPC Reef at João Belo Norte mine. Dashed lines delineate the trajectory of high-grade zones, which align subparallel to the modeled faults. It's important to note that the modeled fault planes represent a subset of the broader F2 fault group due to limitations in visual representation.; (b) N-S cross-section zooming in on the mineralized zone showcasing the three-dimensional layout of galleries within the underground workings of João Belo mine, color-coded to reflect gold grade values obtained through Radial Basis Function interpolation. Additionally, a representative modeled fault F2b, derived from underground data, is depicted. Arrows accompanied by dashed lines indicate the plunge direction of mineralization, which aligns with the modeled faults and varies between 40° and 60° SE. (c) N-S section view of the maximum intensity projection of gold grades from drill holes and channel samples from mines within the Northern Domain. Dashed lines denote areas with a higher concentration of high-grade samples.....52

Fig. 14. Three-dimensional model of the metaconglomerate bodies at Canavieiras Sul mine, generated from drill hole data and underground gallery mapping. It's worth noting that samples with the highest grades, collected from drill holes and represented by colored bars, are typically located at the top of the mineralized Reefs. In the image: MSPC Reef in green, LVLPC Reef in light blue, MU Reef in gold, and LU Reef in gray.....54

Fig. 15. (a) Dendritic gold on fracture plane in samples collected at level N270 of Morro do Cuscuz mine; (b) Placer gold on fracture plane in sample collected at Canavieiras Central mine; (c) Gold associated with fuchsite in the matrix and filling fractures in core sample (drill hole MVTEX00189); (d) Reflected light photomicrography of gold associated with pyrite (Py) in sample GSR-P14-L1, collected at João Belo mine. (e) Reflected light photomicrography of gold nuggets filling interstices between quartz grains in the matrix, sample GSR-P5-L1; (f) Reflected light photomicrography of gold filling microfractures in sample GSR-5-L.....55

Fig. 16. (a) 1- Two-dimensional slice image of sample GSR-P6-L2, artificially colored, highlighting in yellow the class of Sulfide 1, with attenuation profile A-A' traced over the red line; 2- Attenuation profile A-A' showing the response of the different constituent elements of the sample. Peak heights are directly proportional to the density of the material penetrated by X-ray beams; 3- Digital number histogram used for the segregation of grayscale bands representing each constituent mineral of the sample; (b) 1- Two-dimensional slice image of sample GSR-CAC-N130, artificially colored, highlighting in yellow the class of gold, with attenuation profile B-B' traced over the red line; 2- Attenuation profile B-B' showing the response of the different constituent elements of the sample. Peak heights are directly proportional to the density of the material penetrated by X-ray beams; 3- Digital number histogram used for the segregation of grayscale bands representing each constituent mineral of the sample.....57

Fig. 17. (a) Three-dimensional reconstruction of sample GSR-P6-L2 showing the relationship between Gangue (gray), Sulfide 1 (blue), and Gold (yellow) groups. Note the fine gold grains associated with sulfides and within the matrix; (b) Two-dimensional slice image of sample GSR-P6-L2, artificially colored to highlight the Sulfide 1 class in yellow and the Gold class in green, with emphasis on a subhedral pyrite grain containing gold within it.....58

Fig. 18. (a) Three-dimensional reconstruction of sample GSR-CAC-N130 showing the relationship between Sulfide 1 group (blue) and Gold (yellow). Note the fine gold grains associated with sulfides, both within the matrix and within the fractures, as well as coarse and elongated grains filling fracture 1; (b) 1- Three-dimensional image focusing solely on the gold group in sample GSR-CAC-N130, highlighting the grains filling fracture 1; 2- Three-dimensional image focusing solely on the gold group in sample GSR-CAC-N130, emphasizing the grains filling fracture 2 and their spatial relationship with fracture 1; (c) 1- Two-dimensional digital slice image of sample GSR-CAC-N130 showing gold grains (white) within altered pyrite crystals (lilac); 2- Detail of the three-dimensional reconstruction of sample GSR-CAC-N130 depicting the relationship between Sulfide 1 group (blue) and Gold (yellow).....59

Fig. 19. (a) Schematic drawing of the rift phase during the formation of the Jacobina basin ; (b) Schematic section of the compressive phase that led to the inversion of the Jacobina Basin in the Paleoproterozoic and culminated in the formation of the Contendas-Jacobina Lineament (adapted from Teixeira et al., 2001); (c) Schematic drawing of the current configuration of the Jacobina Range and its basement, illustrating the main structures mapped in the study area.....63

Fig. 20. (a) Three-dimensional structural model of the Jacobina Mining District region, generated from data collected on the surface, underground, and drill holes, illustrating the main structures mapped in the area, their truncation relationships, and kinematics; (b) Three-dimensional geological model of the Jacobina Mining District area, generated from data collected on the surface, underground, and drill holes, illustrating the main lithotypes found in the region and their relationships.....64

Lista de tabelas

Table 1. Data and parameters applied in the aerogeophysical surveys conducted in the Jacobina Mining District region.....39

Table 2. Comparative table, by domains, of gold grades obtained in drill holes.....51

Sumário

Agradecimentos	18
Resumo	20
Lista de Figuras	24
Lista de tabelas	27
Capítulo 1 – Introdução e Objetivos	15
1. 1 Introdução.....	15
1.2 Objetivos.....	19
1.3 Estrutura da dissertação	19
Capítulo 2 – Materiais e métodos.....	20
2.1 Trabalhos de campo e coleta de amostras	20
2.2 Geoquímica.....	21
2.3 Petrografia	21
2.4 Microtomografia Computadorizada de Raios-X	21
2.5 Análise estrutural.....	22
2.6 Modelagem Tridimensional.....	23
Capítulo 3 - Manuscrito	26
Critical Parameters of a Mineral System and Their Influence on the Formation of High-Grade Ore-Shoots: A Case Study in the Gold District of Jacobina	26
3.1 Introduction	27
3.2 Geological Setting	29
3.2.1 Geotectonic context	29
3.2.2 The Jacobina Group.....	30
3.2.3 Gold Mineralization at the Jacobina Mining District	33
3.3. Materials and methods.....	36
3.3.1 Field works and sampling.....	36
3.3.2 Geochemistry	36

3.3.3 Petrography.....	37
3.3.4 X-Ray Computed Microtomography (Micro-CT).....	37
3.3.5 Structural Analysis	38
3.3.6 Modelling	38
3.4 Results	40
3.4.1 Structural Analysis	40
3.4.2 Structural Domains.....	46
3.4.3 Gold mineralization in the structural domains	50
3.4.4 High-grade zones characterization	54
3.5 Discussion.....	60
3.5.1 Structural evolution	60
3.5.2 The Jacobina Mineral System.....	64
3.5.3 Fertility	65
3.5.4 Geodynamics	66
3.5.5 Architecture	67
3.5.6 Preservation	69
3.5.7 The Jacobina Mineral System Dynamics	69
3.6 Conclusions	71
3.7 Acknowledgements	72
3.8 References	72
Capítulo 4 – Considerações finais	76

Capítulo 1 – Introdução e Objetivos

1. 1 Introdução

Depósitos do tipo paleoplacer, especialmente os metaconglomerados auríferos, desempenham um papel crucial como fontes primárias de ouro na mineração global desse metal. O Witwatersrand, situado na África do Sul, destaca-se como um exemplo notável, respondendo por aproximadamente 30% de toda a produção mundial de ouro ao longo dos anos (Frimmel, 2020). No Brasil, o distrito aurífero de Jacobina, localizado no Centro-Oeste da Bahia, a cerca de 330 km da capital, Salvador (Fig. 1), representa uma instância relevante desse grupo de depósitos, abrigando uma reserva de cerca de 3 milhões de onças e registrando uma produção anual de cerca de 200 mil onças de ouro (Soares *et al.*, 2020).

O Distrito Mineiro de Jacobina está localizado na Serra de Jacobina, um extenso lineamento tectônico de direção NNE originado durante o Paleoproterozóico como resultado de sucessivos eventos de acreção nas margens dos blocos Arqueanos Gavião, Serrinha e Jequié, responsável pela formação do cinturão orogênico denominado cinturão móvel Itabuna-Salvador-Curaçá (Barbosa e Sabaté, 2004).

A Serra de Jacobina é formada, essencialmente, pelos metassedimentos do Grupo Jacobina, aflorante nas porções central e Oeste da Serra, e pelo *Greenstone Belt* Mundo Novo, limitado a porção Leste da mesma (Reis, *et al.*, 2021). Os blocos Gavião, Mairi, e o Complexo Saúde, constituem o embasamento na região, sendo o primeiro localizado a Oeste, em contato tectônico com a Formação Serra do Córrego, base do Grupo Jacobina, e os demais localizados a Leste da Serra, em contato tectônico com a Formação Serra da Paciência, topo do Grupo Jacobina, e com o *Greenstone Belt* Mundo Novo (Pearson *et al.* 2001).

A mineralização aurífera está associada majoritariamente ao Grupo Jacobina, em especial aos metaconglomerados da Formação Serra do Córrego, e ocasionalmente à Formação Rio do Ouro, além de rochas intrusivas máficas e ultramáficas. A Formação Serra do Córrego (LEO *et al.*, 1964) possui uma espessura média total de 1000 metros, sendo subdividida em três subunidades (Molinari *et al.* 1988): metaconglomerado inferior, quartzito intermediário e metaconglomerado superior. No distrito mineiro, os metaconglomerados são denominados "*Reefs*", fazendo alusão à terminologia utilizada

no depósito de Witwatersrand, com a diferença de que, em Jacobina, nem todo *Reef* é mineralizado.

O desenvolvimento dos depósitos minerais é regido por uma série de fatores críticos, os quais desempenham papéis essenciais no processo de mineralização. São eles: uma fonte fértil (fertilidade) associada a uma arquitetura crustal que favoreça a percolação de fluidos mineralizados (arquitetura). Tais fluidos, impulsionados por gatilhos geotectônicos transientes (geodinâmica), ascendem na crosta até atingirem um ponto de acumulação, preservado ao longo dos eventos geológicos subsequentes (preservação).

A associação com estruturas de escala litosférica é um aspecto recorrente na formação da maioria dos depósitos gigantes ou de classe mundial. Existem evidências que indicam uma relação entre taxas elevadas de soerguimento e alterações químicas que propiciam a deposição de ouro. Estruturas de primeira ordem são consideradas como condutos ideais para a ascensão de fluidos mineralizados desde sua fonte até os pontos de deposição e concentração. Por outro lado, estruturas de segunda e terceira ordem, formadas em fases deformacionais precoces e reativadas posteriormente, desempenham um papel crucial na interconexão dos sistemas de falhas, contribuindo para a circulação dos fluidos mineralizados através do aumento da permeabilidade.

Além das estruturas, os fatores intrínsecos, como as características das rochas hospedeiras e suas encaixantes, exercem influência significativa. Destaca-se, sobretudo, as propriedades reológicas destas rochas. O comportamento distintivo das sequências rochosas diante da deformação pode facilitar ou dificultar a circulação de fluidos. Rochas mais competentes, com resposta rúptil à deformação, tendem a tornar-se reservatórios mais eficientes devido à permeabilidade gerada por seu fraturamento. Em contraste, rochas menos competentes, devido a seu comportamento dúctil, atuam como barreiras de permeabilidade, impedindo a saída de fluidos mineralizados dos sistemas hidrotermais. No caso das rochas sedimentares, características texturais como granulometria, maturidade textural e mineralógica, e empacotamento, desempenham um papel crucial na determinação da permeabilidade e porosidade, influenciando assim sua capacidade de armazenamento e circulação de fluidos (Groves *et al.*, 2016, 2020).

A investigação dos parâmetros críticos do sistema mineral na região do Distrito Mineiro de Jacobina é essencial para discernir os controles que influenciam a formação de zonas de alto teor. Isso permite a formulação de modelos prospectivos precisos e a otimização das etapas do processo produtivo em escala de mina. Entretanto, a maioria das

pesquisas realizadas no depósito de Jacobina se concentram no extenso debate entre defensores de uma origem detrítica, em um modelo de deposição do ouro associado a um sistema de paleoplacer (Bateman, 1958; Cox, 1967; Gross, 1968; Garayp and Frimmel, 2023), e aqueles que defendem uma origem epitermal (White, 1961; Davidson, 1957; Ledru *et al.*, 1997; Milesi *et al.*, 2002; Teixeira *et al.*, 2001, 2010, 2019).

Sob a ótica econômica, estudos voltados para a compreensão holística da geometria do depósito e, principalmente, dos fatores que controlam a formação de zonas de alto teor, são fundamentais para a gestão eficiente de programas exploratórios e de lavra. Esses programas se valem do conhecimento geológico e da compreensão dos padrões de mineralização como orientação para as atividades mineradoras.

Em Jacobina, os desafios na elucidação dessas questões são notavelmente significativos, devido à ausência de características distintivas entre os metaconglomerados mineralizados e os estéreis, além da intensa deformação regional e da presença de estruturas geradas em múltiplos eventos tectônicos. Isso torna a identificação de zonas de alto teor uma tarefa complexa em todas as escalas. Além disso, a homogeneidade composicional das rochas, predominantemente constituídas por quartzo, diminui a eficácia de métodos indiretos de pesquisa, como geofísica e *footprint* geoquímico, na identificação de vetores exploratórios e das zonas mineralizadas de alto teor.

Diante desses desafios, a tecnologia emerge como uma aliada crucial, possibilitando uma avaliação abrangente e multidimensional dos extensos bancos de dados gerados ao longo de décadas de mapeamentos e amostragens de superfície e subsolo. Técnicas analíticas de modelagem e visualização 3D facilitam a integração de informações litoestruturais de superfície e subsuperfície, permitindo a visualização tridimensional da geometria dos corpos mineralizados e da arquitetura de sistemas mineralizantes. Cowan (2014, 2022), evidenciou que, em depósitos com uma grande quantidade de informações de tores, é possível interpretar padrões e controles estruturais a partir destes dados, culminando na identificação de padrões geométricos importantes para a compreensão da mineralização em escala de depósito. Andrew (2020), aplicou técnicas de interpolação de dados isotópicos de Oxigênio associadas a modelagem tridimensional de estruturas e litologias no depósito de Cobre de Mount Isa, Austrália, para identificar, com sucesso, os controles e a geometria das regiões de alto teor a partir da compreensão dos caminhos pelos quais os fluidos mineralizados circularam e se

concentraram, possibilitando a identificação de possíveis alvos de alto teor. Da mesma forma, técnicas de microscopia tridimensionais, como a microtomografia computadorizada de raios-X (micro CT), podem fornecer informações em 3D que ressaltam aspectos texturais importantes para o entendimento de variados depósitos e estilos de mineralizações (Cnudde *et al.*, 2013; da COSTA *et al.*, 2022).

Nesta pesquisa será apresentado um estudo tridimensional em diferentes escalas das zonas de alto teor de depósitos do Distrito Mineiro de Jacobina, com o intuito de identificar os parâmetros críticos associados ao sistema mineralizante, incluindo as principais estruturas controladoras da percolação e deposição de fluidos mineralizados (condutos e trapas) e as características composicionais e texturais das zonas de alto teor (reservatórios e capeadores). Para tanto serão realizadas modelagens tridimensionais desde a escala microscópica até a escala regional, visando compreender a geometria dos corpos mineralizados e a arquitetura do sistema mineralizante.

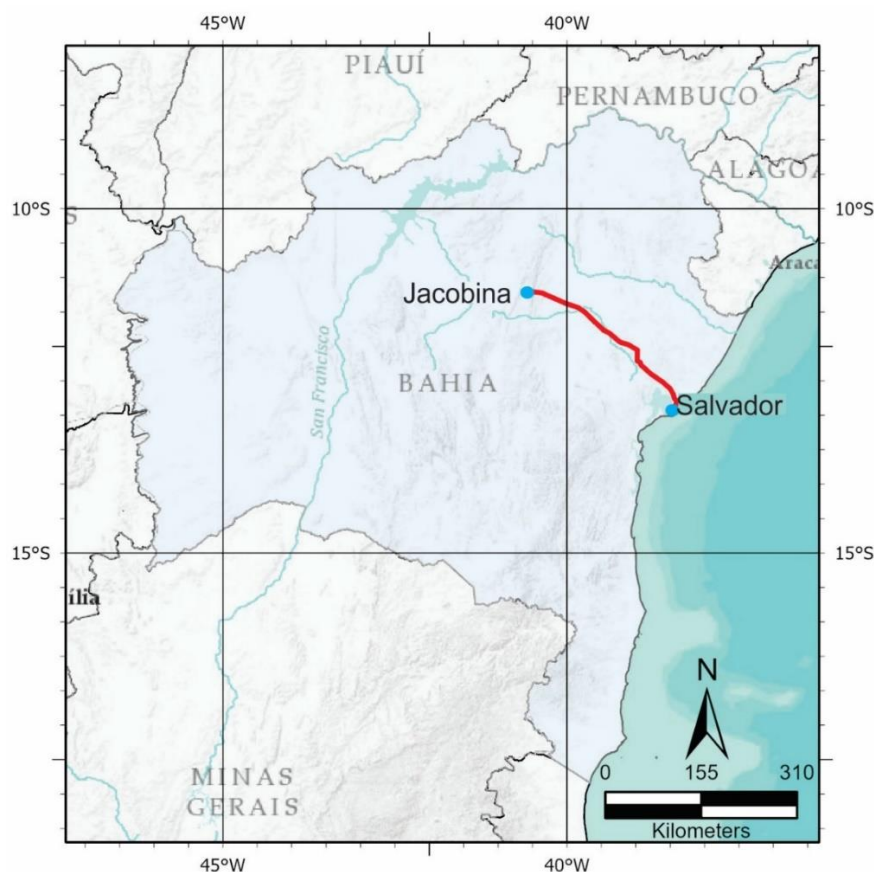


Fig. 1. Mapa de localização do município de Jacobina

1.2 Objetivos

O objetivo desta pesquisa é identificar os parâmetros críticos envolvidos na formação dos corredores de alto teor do Distrito Mineiro de Jacobina, a partir da análise estrutural e modelagem tridimensional em várias escalas, visando compreender a arquitetura do sistema mineralizante e gerar vetores prospectivos para a exploração de ouro na região da Serra de Jacobina. Os objetivos específicos incluem:

- (i) Identificação e mapeamento das estruturas regionais que possam ter funcionado como condutos de fluidos mineralizantes a partir de interpretação de dados aerogeofísicos e integração de dados regionais;
- (ii) Realização de perfis regionais, em escala 1:25.000, transversais a estruturação da Serra de Jacobina, visando a coleta de elementos estruturais, a análise cinemática e o entendimento do arcabouço estrutural regional;
- (iii) Mapeamento de detalhe (1:5.000) em superfície nas minas de Serra do Córrego, Morro do Vento, João Belo e Canavieiras para caracterização geométrica e textural dos corpos metaconglomeráticos e identificação do arcabouço estrutural destas minas;
- (iv) Trabalhos de campo em galerias das minas subterrâneas de Canavieiras, João Belo e Morro do Vento para identificação das principais estruturas e características texturais originais e secundárias dos metaconglomerados nas zonas de alto teor;
- (v) Análise microscópica tridimensional das zonas de mais alto teor, visando identificar os aspectos texturais primários e secundários e compreender a distribuição do ouro em zonas de mais alto teor, por meio da microtomografia computadorizada;
- (vi) Modelagem tridimensional dos dados estruturais, litológicos e de teores de ouro, de superfície e subsuperfície, para reconhecimento de padrões de distribuição de ouro, compreensão do comportamento da mineralização nas diferentes minas do Distrito Mineiro de Jacobina e delineação da arquitetura do sistema mineralizante.

1.3 Estrutura da dissertação

Esta dissertação de mestrado, desenvolvida no programa de Pós-graduação em Geologia da Universidade de Brasília, sob a orientação da Professora Dra. Catarina Labouré Bemfica Toledo, no contexto Grupo de Pesquisa CNPq – Geodinâmica de

Terrenos Pré-Cambrianos e Sistemas Minerais Associados (SisMineral), e coorientação do Professor Dr. Farid Chemale Jr. Ela está compartimentada em três capítulos. O primeiro capítulo trata da apresentação da área de estudo e traz uma breve contextualização da geologia regional e local do Distrito Mineiro de Jacobina. O segundo capítulo compreende os materiais e métodos aplicados neste trabalho. O Terceiro capítulo traz os resultados obtidos, discussões e conclusões deste trabalho um formato de um artigo intitulado *“Parâmetros críticos de um sistema mineral e sua influência sobre a formação de corredores de alto teor: um estudo de caso no Distrito Aurífero de Jacobina”*, a ser submetido após a defesa. O quarto e último capítulo finaliza esta dissertação com as considerações finais e algumas sugestões para trabalhos futuros.

Capítulo 2 – Materiais e métodos

2.1 Trabalhos de campo e coleta de amostras

Os trabalhos de campo foram iniciados em superfície, com realização de perfis regionais, em escala 1:25000, transversais a estruturação da Serra de Jacobina, visando a coleta de elementos estruturais, tais como geometria e cinemática que possam contribuir para o entendimento do arcabouço estrutural regional. Em subsolo, os trabalhos foram focados em pontos específicos das galerias subterrâneas das minas Canavieiras e João Belo, considerados, em análise prévia baseada em amostragens de canal e teores de furos de sondagem, representativos de zonas mineralizadas de alto teor e estéreis, onde foram coletados dados, litológicos, estruturais e amostras orientadas para fins de comparação dos aspectos texturais presentes nas zonas de mais alto teor com aquelas existentes em zonas de teor baixo ou estéreis. Nesta fase, foram mapeados 17 pontos, sendo 11 na mina Canavieiras e 6 na mina João Belo Norte, onde foram coletadas 28 amostras consideradas representativas dos pontos mapeados. Ao todo, foram preparadas 31 lâminas delgadas polidas para estudo das características microscópicas das amostras obtidas em subsolo. Quatro amostras foram selecionadas para o estudo de microtomografia computadorizadas de Raios-X, dentre as quais duas foram de fato submetidas ao teste.

Os trabalhos de campo foram realizados em duas campanhas específicas para coleta de amostras e dados estruturais, complementadas por mapeamentos geológico-estrutural sistemático, em escala 1:5000 de alvos e minas durante a rotina de trabalho do autor, como parte da equipe de exploração do Distrito Mineiro de Jacobina. A metodologia utilizada foi a usual em terrenos metamórficos e envolveu a medição de

elementos estruturais planares e lineares pelo método de *dip direction* (Mcclay, 1987), descrição e análise cinemática de estruturas, descrições litológicas, confecção de perfis geológicos em várias direções, coleta de amostras orientadas e documentação das observações através de desenhos e fotografias.

2.2 Geoquímica

Dentre as amostras coletadas em subsolo, 22 foram submetidas a análises geoquímicas de rocha total e *fire assay* no laboratório ALS, unidade Vespasiano, Minas Gerais, Brasil. Nas análises de rocha total, os elementos maiores e metais base foram analisados por Espectrometria de Massa por Emissão Atômica (ICP-AES), enquanto elementos menores e terras-raras foram quantificados por Espectrometria de Massa com Plasma Acoplado (ICP-MS). A determinação do teor de ouro foi realizada com abertura por fusão *fire assay* e quantificação Espectrometria de Absorção Atômica (AAS), em amostras com teores de até 10ppm. Nas amostras com teores superiores a 10ppm, a quantificação foi realizada por gravimetria.

2.3 Petrografia

Com as amostras coletadas em subsolo, foram preparadas 21 lâminas delgadas polidas, quando possível, orientadas, a fim de realizar análises petrográficas e de microtectônica em microscópio óptico. As lâminas também foram submetidas a análises em microscópio eletrônico de varredura (MEV), visando reconhecer padrões texturais e microestruturas. Todos os equipamentos utilizados encontram-se nas dependências do Instituto de Geociências da Universidade de Brasília.

2.4 Microtomografia Computadorizada de Raios-X

Dentre as amostras coletadas em subsolo para laminação, duas foram selecionadas para realização de ensaios de Microtomografia Computadorizada de Raios-X (Micro-CT). Este método se baseia na atenuação, por absorção ou espalhamento, de feixes planares de raios-x promovida pelos minerais presentes nas amostras. Esta atenuação é, geralmente, dada pela energia dos feixes de raios-x e a densidade ou número atômico dos compostos imageados (Kyle and Ketcham, 2015). A aquisição dos dados é feita em fatias bidimensionais, de forma a gerar valores em escala de cinza, correspondentes aos coeficientes de atenuação de cada material atravessado pelo feixe numa fatia específica. Centenas de feixes são, então, disparados contra a amostra a partir de diversas posições diferentes, gerando um grande número de fatias, que, na etapa de processamento dos

dados, são reconstituídas gerando a visualização, em três dimensões, da amostra e de seus constituintes, segregados por seu coeficiente de atenuação e, indiretamente, por sua densidade.

O produto primário do escaneamento com resolução de 16 bits é, então, um histograma representativo dos coeficientes de atenuação dos materiais presentes na amostra imageada traduzidos em números digitais constituintes de uma escala de cinza (0 a 255), apresentado em um gráfico de frequência versus números digitais de todos os pixels gerados na análise, permitindo segregar fases minerais com números digitais e, conseqüentemente, coeficientes de atenuação similares utilizando-se as inflexões da curva histogramica.

A escolha das amostras para esta análise baseou-se, principalmente, no equilíbrio entre quantidade de matriz e seixos, possibilitando a avaliação da trama textural em três dimensões, da relação e a disposição dos sulfetos frente a matriz e ao ouro e, das formas de ocorrência do metal em zonas de diferentes teores. Um dos fatores limitantes para a micro-CT é o tamanho e o formato dos objetos a serem testados, pois devem adequar-se, respectivamente, ao espaço disponível na câmara de aquisição dos equipamentos e ao formato cilíndrico do campo de escaneamento (Kyle and Ketcham, 2015). Portanto, as amostras submetidas a este método foram serradas e polidas até atingir diâmetro e altura máximos de uma polegada.

Neste trabalho, as imagens e dados de microtomografia foram obtidas utilizando-se um microtomógrafo SkyScan 1172, da fabricante Bruker. Os parâmetros de aquisição foram: voltagem da fonte de 100kV, corrente da fonte de 100 μ A, filtro de Cu+Al, aquisição em 360° com estágios de rotação de 0.3°. O processamento dos dados foi realizado com os softwares NRECON e CTVOL, ambos fornecidos pela fabricante do equipamento. Todas as análises foram realizadas pelo Laboratório de Propriedades Físicas das Rochas, da Universidade de Brasília.

2.5 Análise estrutural

Em campo, tanto em superfície quando em subsolo, foram coletados 328 dados estruturais planares e lineares e realizada a análise cinemática das estruturas observadas. Os dados foram tratados em conjunto com um banco de dados estrutural, constituído por 45.191 estruturas, incluindo falhas, foliações, veios, brechas, diques e zonas de cisalhamento, gerido pela equipe de geologia de mina atuante no Distrito Mineiro de

Jacobina e foram gerados produtos como estereogramas, análise de paleotensores utilizando o software Faultkin 8 (Marret and Allmendinger, 1990; Allmendinger *et al.*, 2012). É importante ressaltar que as estruturas obtidas nos bancos de dados que não foram coletadas ao longo deste trabalho, foram utilizadas para visualização e compreensão da geometria dos corpos e para fins de modelagem, não sendo aplicadas para o entendimento da evolução tectônica. Posteriormente, foi realizada a individualização de domínios estruturais, com base na relação entre os elementos planares e lineares e afinidade estrutural, visando o entendimento da arquitetura do cinturão. A análise estrutural realizada neste trabalho teve caráter meramente qualitativo, restringindo-se à análise descritiva e cinemática dos elementos estruturais. Neste contexto, foram individualizados grupos de estruturas geneticamente e temporalmente relacionados, que caracterizam determinada fase de deformação (Turnes e Weiss, 1963). Cada fase de deformação corresponde, portanto, ao intervalo de tempo no qual tais estruturas foram geradas. A idade relativa das estruturas foi estabelecida com base nos seguintes critérios: i. critérios clássicos de corte e superposição de estruturas (Hobbs, Means and Williams, 1976); ii. campo de tensões nos quais essas estruturas foram formadas; e iii. nível crustal de formação.

2.6 Modelagem Tridimensional

Os dados coletados nos trabalhos de campo, somados aos dados geológicos e estruturais e de teores disponíveis no banco de dados da Jacobina Mineração e Comércio, foram utilizados na elaboração de modelos geológico-estruturais e modelagem de zonas de alto teor, permitindo avaliar a existência de corredores de alto teor e suas correlações com as estruturas e rochas hospedeiras, possibilitando compreender a arquitetura do depósito e sua influência sobre a concentração de minério. Para a elaboração dos modelos supracitados, foi utilizado o Software LeapFrog Geo, versão 2022.1.

Os modelos gerados foram:

- Interpolação de teores de amostras de canal de todas as minas do Distrito Mineiro de Jacobina, utilizando-se o banco de dados da empresa, que contém, ao todo, 214.212 amostras. A amostragem de canal é realizada rotineiramente pela equipe de geologia de mina, acompanhando o desenvolvimento das frentes de lavra das minas do Distrito, o que resulta em canais que distam aproximadamente 3m entre si. Em cada canal são coletadas amostras de rocha com comprimentos entre 25cm e 50cm, posteriormente submetidas a análises de Fire Assay para determinação do teor de ouro.

A interpolação foi realizada no software LeapFrog Geo utilizando a ferramenta de interpolação de Função de Base Radial (RBF), com interpolador linear, sem a aplicação de trends de tendência e removendo-se as amostras sem resultados. Também não foram utilizados valores de *capping*.

O resultado da interpolação foi subdividido em oito intervalos de teores, cujas cores atribuídas para cada intervalo foram utilizadas para identificar, nas triangulações de galerias de minas, as zonas de baixos, médios e altos teores.

- Modelo estrutural individual das minas Canavieiras, Morro do Vento e João Belo, baseado nos dados planares coletados ao longo de décadas de mapeamentos sistemáticos de galerias pela equipe de Geologia de Mina de Jacobina, que conta, até o momento, com 45.191 estruturas, incluindo falhas, foliações, veios, brechas, diques e zonas de cisalhamento, e nos 328 dados planares e lineares coletados durante esta pesquisa.

Nesta etapa, foram modeladas apenas estruturas consideradas significativas para a interpretação dos fatores controladores da mineralização, principalmente aquelas visivelmente associadas a zonas de alto teor.

- Modelo estrutural regional baseado em banco de dados de pontos coletados pelas equipes de exploração em Jacobina, constituído de 8766 pontos, onde foram coletados dados litológicos e estruturais, e em sensoriamento remoto utilizando imagens de radar (SRTM) e satélite (CBERS 4^a), associados a dados de levantamentos aerogeofísicos magnéticos e radiométricos.

Os principais lineamentos regionais foram traçados utilizando-se imagens SRTM de resolução espacial 15m, CBERS 4a com resolução espacial de 2m, e imagem da derivada *tilt* dos dados magnéticos obtidos por aerogeofísica. O resultado do canal do Tório (Th), obtido a partir dos dados radiométricos coletados, foi utilizado para definir os limites da bacia de Jacobina e seu contato com o embasamento através do sistema de falhas de Jacobina, a Oeste, e sistema de falhas de Pindobaçu, a Leste.

- Modelos litológico-estruturais regional e das minas do Distrito Mineiro de Jacobina, baseado em dados de mapeamentos lito-estruturais em superfície e subsolo, e de furos de sondagem diamantada realizados ao longo dos anos pelas empresas detentoras dos direitos minerários do Distrito. Os bancos de dados contam com 36712 pontos de mapeamento em subsolo, realizados nas frentes de desenvolvimento das galerias das minas subterrâneas, 8766 pontos de mapeamentos em superfície, realizados ao longo da

extensão da Serra de Jacobina, e 8451 furos de sondagem diamantada, totalizando 1114025 metros perfurados na área do Distrito Mineiro.

- Criação de renderizações de projeções de máxima intensidade de teores de amostras de canais das minas subterrâneas para visualização de padrões geométricos e controle das zonas de alto teor.
- Criação de renderizações de projeções de pontos médios de intervalos de litologias descritas em furos de sondagem para visualização de padrões geométricos dos corpos metassedimentares nas diferentes minas do Distrito Mineiro de Jacobina.

Capítulo 3 - Manuscrito

Critical Parameters of a Mineral System and Their Influence on the Formation of High-Grade Ore-Shoots: A Case Study in the Gold District of Jacobina

Gabriel S. Seidler¹, Catarina B.L. Toledo¹, Beatriz D. R. Almeida¹, Farid Chemale Jr.²

¹Instituto de Geociências, Universidade de Brasília, Brasília, Brasil

²Programa de Pós-Graduação em Geologia, Universidade do Vale do Rio dos Sinos, São Leopoldo, Brasil

Abstract

Understanding the factors that control the formation of high-grade mineralization zones is crucial for optimizing exploration and mining efforts. This study investigates mineral systems concepts and their application in unraveling the key controls on high-grade zones at the deposit scale in the gold-bearing Jacobina Mining District, which contains 10 million ounces. To understand the controls governing the circulation of fluids that remobilized gold, accumulated and concentrated gold mineralization, we integrated data collected from surface mapping and underground mine surveys, petrography and Micro-Computed Tomography (Micro-CT) to produce three-dimensional geological-structural models with maximum intensity projections and gold grade interpolations. Based on these studies, the first-order structures, predominantly N-S oriented plunging to east, parallel to metaconglomerate reefs, acted as conduits for mineralized fluids, facilitating their circulation through host rocks throughout the Jacobina Mining District. Second-order structures, oriented E-W, functioned as permeability barriers or low-pressure zones, leading to the accumulation of mineralized fluids at the intersections with first-order structures, ultimately forming regions of high gold concentration in all studied structural domains. In the Canavieiras mines, antiformal structures served as important fluid accumulation zones, resulting in higher gold grades compared to the other mines of the Jacobina District. The findings contribute to a refined exploration model, offering valuable guidelines for future exploration and resource development.

Key words: Mineral Systems; Gold high grade ore shoots; 3D Modelling; X-Ray Computed Microtomography; Jacobina Mine.

3.1 Introduction

Paleoplacer-type deposits, particularly Au(U)-bearing quartz metaconglomerates, are significant gold sources for global mining, with the most prominent example being the Witwatersrand in South Africa. This region has produced approximately 30% of all the gold ever mined worldwide (Frimmel, 2020). In Brazil, the Jacobina gold district in Bahia state, Northeastern Brazil, is a primary example, holding reserves of about 10 million ounces and producing around 200,000 ounces annually (Soares et al., 2020). These deposits are directly linked to the Archean atmosphere, hydrosphere, and biosphere (Hoffman, 2024), where an anoxic environment played a crucial role in the deposition of the Au(U)-quartz conglomerates (e.g., Frimmel, 2005; Heinrich, 2015; Teles et al., 2020; Frimmel, 2023; Hoffman, 2204). Subsequent geological processes have modified the original geometry and trends of the Au(U) mineralization, resulting in various Au-pyrite parageneses (da Costa et al., 2020; Teles et al., 2020). These insights support hybrid genetic models for these deposits, combining placer and hydrothermal processes becoming a very complex mineral deposit.

In the Jacobina Mining District, gold mineralization occurs in the Jacobina Group, more precisely to the quartz metaconglomerates of the Serra do Córrego Formation, and occasionally to the Rio do Ouro Formation and mafic and ultramafic intrusive rocks. The Serra do Córrego Formation (LEO et al., 1964) has a total average thickness of 1000 meters, which was subdivided into three subunits: lower metaconglomerate, intermediate quartzite, and upper metaconglomerate (Molinari et al., 1988).

At Jacobina, both mineralized and barren metaconglomerates are referred to as Reefs, alluding to the nomenclature used in the Witwatersrand deposit. Like these deposits, its main characteristic is the presence of gold in metaconglomerates and detrital pyrites with Au(U) indicative of an Archean depositional environment (Teles et al., 2015) with a classic signature of Archean MIF-S isotopic signatures preserved in the detrital pyrites (Teles et al. 2020) who were able to identify different phases of pyrite formation in the Jacobina district through petrographic observations, in situ trace-element analysis, and multiple sulfur isotope analyses (^{32}S , ^{33}S , ^{34}S , and ^{36}S) of pyrite from both alluvial and marine facies. However, as it lies on the margin of a reworked craton (metacraton, Santos et al., 2018), the association of rocks originally deposited in a rift system (Teles, 2015) is deformed by the collision of Archean plates during the Transamazonian-Eburnean Cycle (2.1–1.9 Ga; Ledru et al., 1997; Barbosa and Sabaté, 2004). During this tectonic event,

the four major crustal segments of SFC (Gavião, Jequié, Serrinha and Itabuna-Salvador-Curacá) were juxtaposed, generating a Paleoproterozoic mobile belt in the region (Barbosa and Sabaté, 2004) at margin of the Archean Gavião paleoplate. Thus, Au deposits in conglomerate reefs underwent a gold dispersion and concentration processes, associated with the Paleoproterozoic extensional and compressional events already described by Ledru et al., 1997; Milesi et al., 2002 and Santos et al., 2019 and references therein, making the definition of the geometry of mineralized bodies and their geological control very complex.

Understanding the critical parameters of the mineral system operating in the region where the Jacobina Mining District is located is of paramount importance for understanding the controls acting on the formation of high-grade zones, allowing the generation of assertive prospective models and the optimization of production process steps on a mine scale.

From an economic point of view, studies focused on the deposit geometry and, mainly, the factors controlling the formation of high-grade zones, are essential for the management of efficient exploration and mining programs, which use geological knowledge and understanding of mineralization patterns as guides for mining activities.

In Jacobina, the challenges in elucidating such issues are especially significant, since mineralized metaconglomerates do not present visibly distinctive characteristics from the barren ones and because it is an intensely deformed region, with structures generated in multiple tectonic events, thus complicating the identification of ore and high-grade zones in outcrops, drill holes, and underground galleries. In addition to this, the compositional homogeneity of the rocks in the region, consisting mostly of quartz, significantly reduces the effectiveness of indirect exploration methods, such as geophysics, or the determination of a geochemical footprint for mineralized areas.

Faced with these challenges, technology becomes an important ally, as it allows for a comprehensive and multidimensional evaluation of the robust database generated over decades of surface and subsurface mapping and sampling, and the thousands of lithostructural information collected in diamond drill holes, through analytical and computational techniques that allow, for example, the visualization, via three-dimensional models, of the geometry of mineralized bodies and grades and their spatial arrangement (Cowan et al., 2002, Cowan, 2014, 2020, 2022). In this context, other modern analytical techniques, such as X-ray computed microtomography (micro-CT),

allow for the three-dimensional evaluation of ore minerals and their host rock on a micro to nanometric scale and assist in understanding the processes involved in the deposition and accumulation of gold in high-grade ore shoots (Cnudde et al., 2013; da Costa et al., 2022).

This work addresses complex geological models that involve both syn-depositional and post-depositional processes in environments such as anoxic sedimentation settings. These processes include syn-depositional basin-forming tectonics and the percolation of mineralizing fluids, as well as diagenesis ranging from early to late stages and tectonic modifications associated with orogenic events, which involve various deformational events under different metamorphic conditions. Thus, we present an integrated approach using surface and subsurface geological mapping, petrography, micro-CTto, and 3-D modelling were applied to the gold mineralization in the Jacobina Mining District, focusing on the structural and dynamic analysis of the factors controlling the generation of high-grade zones. So, we have a better evaluation of the role of structures in the remobilization and re-concentration of gold in high-grade zones, from the perspective of mineral systems.

3.2 Geological Setting

3.2.1 Geotectonic context

The Jacobina Range is part of an extensive tectonic alignment, oriented NNE, with over 500 km in length, situated in the central-eastern region of the state of Bahia. The basement to the basin is constituted by the Paleoproterozoic blocks (3.6 -3.3 Ga) Gavião, Serrinha, Jequié and Itabuna-Salvador-Curaçá, which comprises TTG (Tonalite-Trondhjemite-Granodiorite) suites, granitic gneisses, metabasalts, metagabbros and metarhyolites, as well as the 3.3 Ga metasedimentary rocks of the Mundo Novo Greenstone Belt (Nutman and Cordani, 1993, Martin et al., 1997, Peucat, 2002, Barbosa et al., 2003; Barbosa and Sabaté, 2004; Pearson et al., 2005, Zincone et al., 2016).

The tectonic juxtaposition of the major crustal Paleoproterozoic blocks culminated on the formation of the remarkable Contendas-Jacobina lineament (Sabaté et al., 1990) which represents a Paleoproterozoic collisional suture zone, where fold-thrust deformation and multiple granitic bodies emplacement occurred (Sabaté et al., 1990, Cruz et al., 2016), during the 2.1 – 1.9 Ga Transamazonian-Eburnean cycle (Ledru et al., 1994). The most prominent constituents of the Contendas-Jacobina lineament are the metamorphosed siliciclastic rocks of the Jacobina Group (Fig. 2).

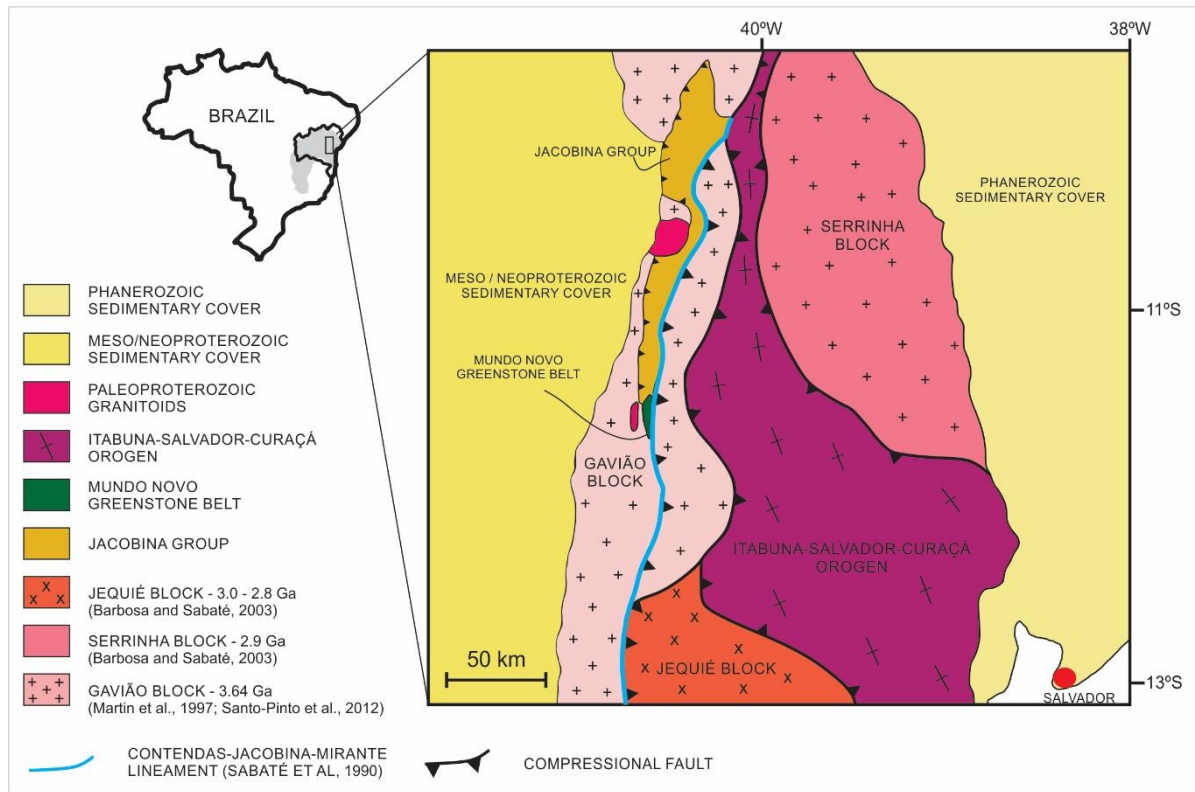


Fig. 2. Schematic sketch of the main geotectonic units present in the northern portion of the Contendas-Jacobina lineament. (Modified from Teles et al., 2017, Reis et al., 2021, dos Santos et al., 2019).

3.2.2 The Jacobina Group

The Jacobina Group (Fig. 3a) comprises the Serra do Córrego, Rio do Ouro, and Serra da Paciência formations (Pearson et al., 2005), essentially consisting of siliciclastic rocks and subordinate metapelites, deposited in a rift-type basin (Mascarenhas et al., 1992; Pearson et al., 2005; Teles et al., 2015, 2020; Reis et al., 2017), whose sediment source would be exclusively the Paleoproterozoic rocks of the Gavião block, according to detrital zircon dating with U-Pb ages ranging from 3.3 to 3.6 Ga (Teles et al., 2015). The current configuration of the layers, in elongated tabular bodies approximately N-S oriented, with dips ranging between 40 and 65 degrees to the east, and the metamorphism in greenschist facies, are results of the Paleoproterozoic orogeny, 2.1-19 Ga (Ledru et al., 1997; Milesi et al., 2002, Santos et al. 2019), which resulted in the formation of the Itabuna-Salvador-Curaçá Belt (Barbosa & Sabaté, 2004).

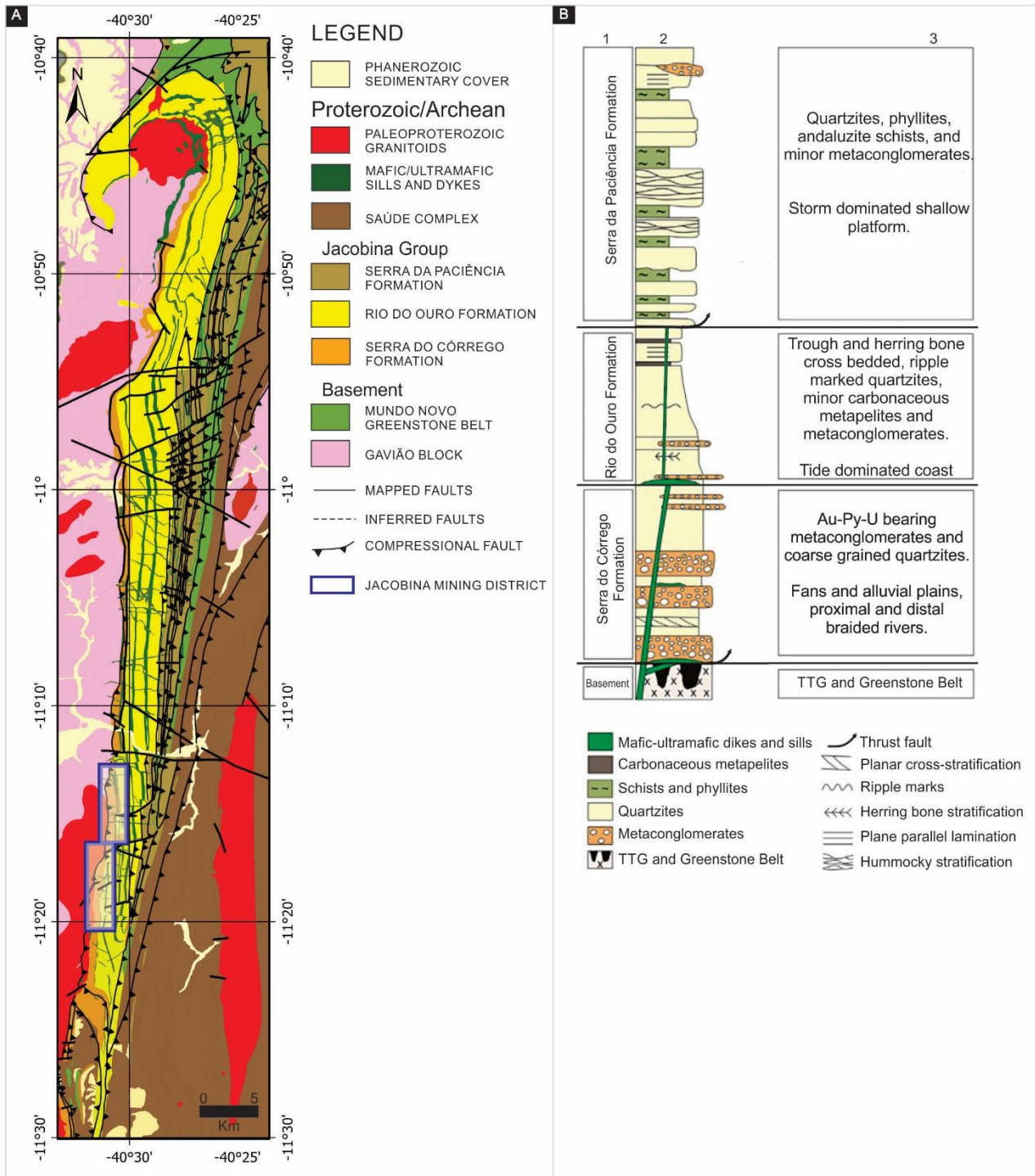


Fig. 3. (a) Geological map of the Jacobina Range. (b) Stratigraphic column of the Jacobina Group. Modified from Teles et al., (2015), Ferreira et al., (2022); Pearson et al., (2005), and Mascarenhas et al., (1998).

The base of the Jacobina Group is characterized by oligomictic metaconglomerates and quartzites of the Serra do Córrego Formation, which outcrop in the western portion of the Jacobina Range. According to Molinari et al. (1988), the formation's stratigraphy consists of two large metaconglomerate packages (lower and upper) separated by an intermediate quartzitic package (Fig. 4). The Lower Metaconglomerate has a discordant contact with the basement and a thickness ranging

between 40 and 200 meters. It is subdivided from the base to the top into four Reefs: Basal Reef, Footwall Reef, Main Reef, and Hangingwall Reef. The intermediate quartzite consists of medium to coarse-grained orthoquartzites with a thickness of 130 to 425 meters, generally exhibiting crossbedding (Pearson et al., 2005). The Upper Metaconglomerate is subdivided into six Reefs named LU Reef, MU Reef, LVLPC Reef, MSPC Reef, Dutch Reef, and Maneira Reef, with a thickness ranging between 120 and 440 meters.

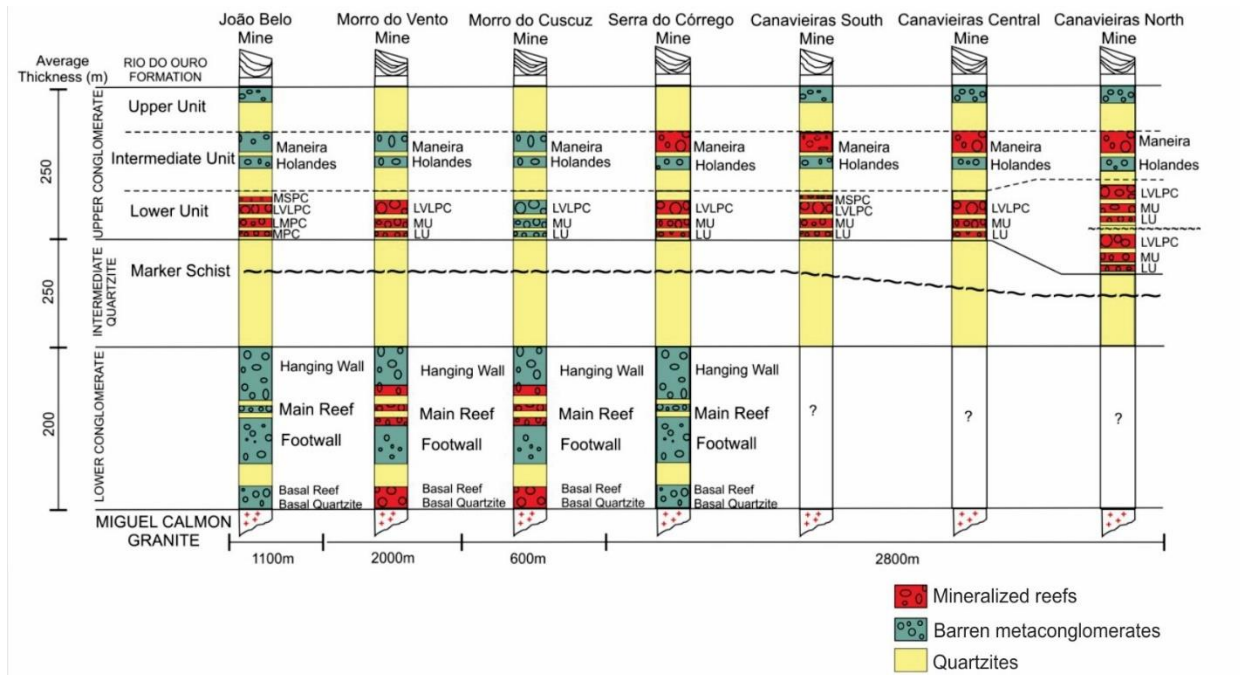


Fig. 4. Comparative stratigraphy of the mines in the Jacobina Mining District and the mineralized metaconglomerate bodies (Reefs) found in each of them. Reproduced from Soares et al., (2020). In the figure, only the bodies under active exploitation are represented in red. Exploratory targets or bodies with unmined mineralization are not depicted.

Gold mineralization occurs in the metaconglomerates called Reefs, in allusion to the Witwatersrand deposit, which are identified and individualized by aspects such as: size and selection of pebbles, packing, matrix characteristics (color, degree of oxidation, presence of sulfides, hydrothermal alterations), and presence of visible gold. The Basal, Main Reef, LU, MU, and LVLPC Reefs stand out for carrying higher grades.

It is worth noting that, unlike the Witwatersrand deposit, the Reefs in Jacobina are not mineralized throughout their extension and thickness. Gold is restricted to centimeter to metric levels contained within the metaconglomerate bodies. These levels are referred to as "resource domains," commonly used to define ore bodies in the mining industry. Additionally, the names given to the Reefs in Jacobina are strictly for industrial and production purposes, without necessarily denoting a geological factor by them.

The Rio do Ouro Formation outcrops in the central ridges of the Jacobina Range in transitional contact with the Serra do Córrego Formation, indicating continuity of the transgression to a shallow marine environment (Pearson et al., 2005). It consists of highly pure orthoquartzites, with high textural and mineralogical maturity, and a thickness of up to 2000 meters (Teles et al., 2015). Sedimentary structures such as asymmetric ripples are common in outcrops of this formation. In this formation, gold mineralization is restricted to fractures and faults, without economic relevance.

The Serra da Paciência Formation is restricted to the eastern portion of the Jacobina Range. This unit consists of thick packages of orthoquartzites, andalusite-quartz-graphite schists, and subordinately, polymictic metaconglomerates, whose pebbles of black metachert, metagraywacke, and quartz suggest the Mundo Novo Greenstone Belt as the source of sediments (Pearson et al., 2005).

Intersecting the metasedimentary sequences of the Jacobina Group, in the extensive N-S trending valleys and in the more restricted E-W trending valleys, are mafic and ultramafic rocks with sill and dyke geometries, partially pre- to syn-tectonic (Pearson et al., 2005). These bodies may locally host gold-mineralized quartz veins, faults, and fractures (Miranda et al., 2021).

3.2.3 Gold Mineralization at the Jacobina Mining District

The Jacobina Mining District is located on the western edge of the homonymous Jacobina Range (Fig. 3a), where exclusively the gold-bearing metaconglomerates of the Serra do Córrego Formation are exploited. The mines of the complex extend for about 10 km following the N-S direction of the metaconglomerates (Fig. 5a), and they present particularities in terms of production. Some mines are concentrated on the lower metaconglomerates, mainly in the Basal and Main Reef Reefs. These mines include Morro do Vento (MVT) and Morro do Cuscuz (MCZ) (Fig. 4). On the other hand, in mines such as Canavieiras Sul (CAS), Canavieiras Central (CAC), Canavieiras Norte (CAN), and Serra do Córrego (SCO), only the upper metaconglomerates are exploited, with a focus on Reefs LU, MU, LVLPC, and Maneira (Fig. 5b). In João Belo Norte mine (JBN), the Reefs of the upper metaconglomerate receive a different nomenclature, with the stratigraphic equivalents of Reefs LU and MU being respectively named MPC and LMPC (Fig. 5c).

Gold mineralization occurs as inclusion of detrital bearing pyrite, hydrothermal pyrite and along then fractures or quartz vein as well as disseminated in the matrix of the metaconglomerates, within pyrites and filling fractures (Teixeira et al., 2001, Teles, 2015, 2020). Within the Reefs, economic gold grades can occur at multiple levels (Fig. 4), with thicker packages presenting mineralized horizons at the top, center, and base of the layer. Teles et al. (2015, 2020) characterized the Au (U)-bearing detrital pyrites deposited under anoxic conditions with Archean S signature. The mineralized bodies exhibit often a hydrothermal paragenesis consisting of pyrite, pyrrhotite, andalusite, fuchsite, quartz, sericite, and tourmaline (Milesi et al., 1996, Teixeira et al., 2001, Teles et al., 2015). Most of the hydrothermal fluid percolation with redistribution and redeposition of gold along with fractures, anamastosed shear zones and veins are connected to the Paleoproterozoic multiple tectonic events affected the Jacobina Group (Milesi et al., 1996; Ledru et al., 1997; Teixeira et al., 2001; Milesi et al., 2002; Pearson et al., 2005, Santos et al., 2019). A detailed description of these tectonic events can be found in Santos et al. (2019).

In addition to the metaconglomerates, the quartzites and mafic and ultramafic intrusive rocks found in the region are also mineralized in gold, usually associated with fractures and quartz veins (Teixeira et al., 2001; Miranda et al., 2021). Although the metal concentrations in these bodies are sub-economic, some artisanal mining operations exploit mineralized quartz veins, mainly in the central-northern portion of the Jacobina Range. According to Miranda et al. (2021), the control of mineralization in mafic and ultramafic intrusive bodies is predominantly structural, with veins oriented in N-S and E-W directions, generated in different phases resulting from the progressive deformation in the Jacobina region.

The source of the mineralization is still subject of debate, and various models have been proposed over the years, starting with the paleoplacer model and detrital origin of gold (Bateman, 1958). Gross (1968) proposed a modified paleoplacer model, where there would be remobilization of detrital gold promoted by the circulation of hydrothermal fluids. Almost simultaneously, White (1961) and Cox (1967) proposed an epithermal origin for mineralization and the concept of a hydrothermal fault-reservoir, which brought with it some precepts of mineral systems, followed by Milesi et al. (2002). Teixeira et al. (2001) and Pearson et al. (2005) suggested an orogenic origin for the geometry of regional shear zones and for the sulfidation of the Reefs, aligned with an epigenetic origin for the

gold in Jacobina. Recently, Teles et al. (2020) and Garayp & Frimmel (2023), shed light on S isotopes evidence suggesting a syngenetic origin for the gold, which would have been deposited as inclusions in syngenetic pyrites, derived from intrabacinal carbonaceous shales (Teles et al. 2020). Currently, the most widely accepted explanation combines placer models (syngenetic) and gold mineralization remobilized by hydrothermal fluids driven by post-depositional events, including the tectono-metamorphic events.

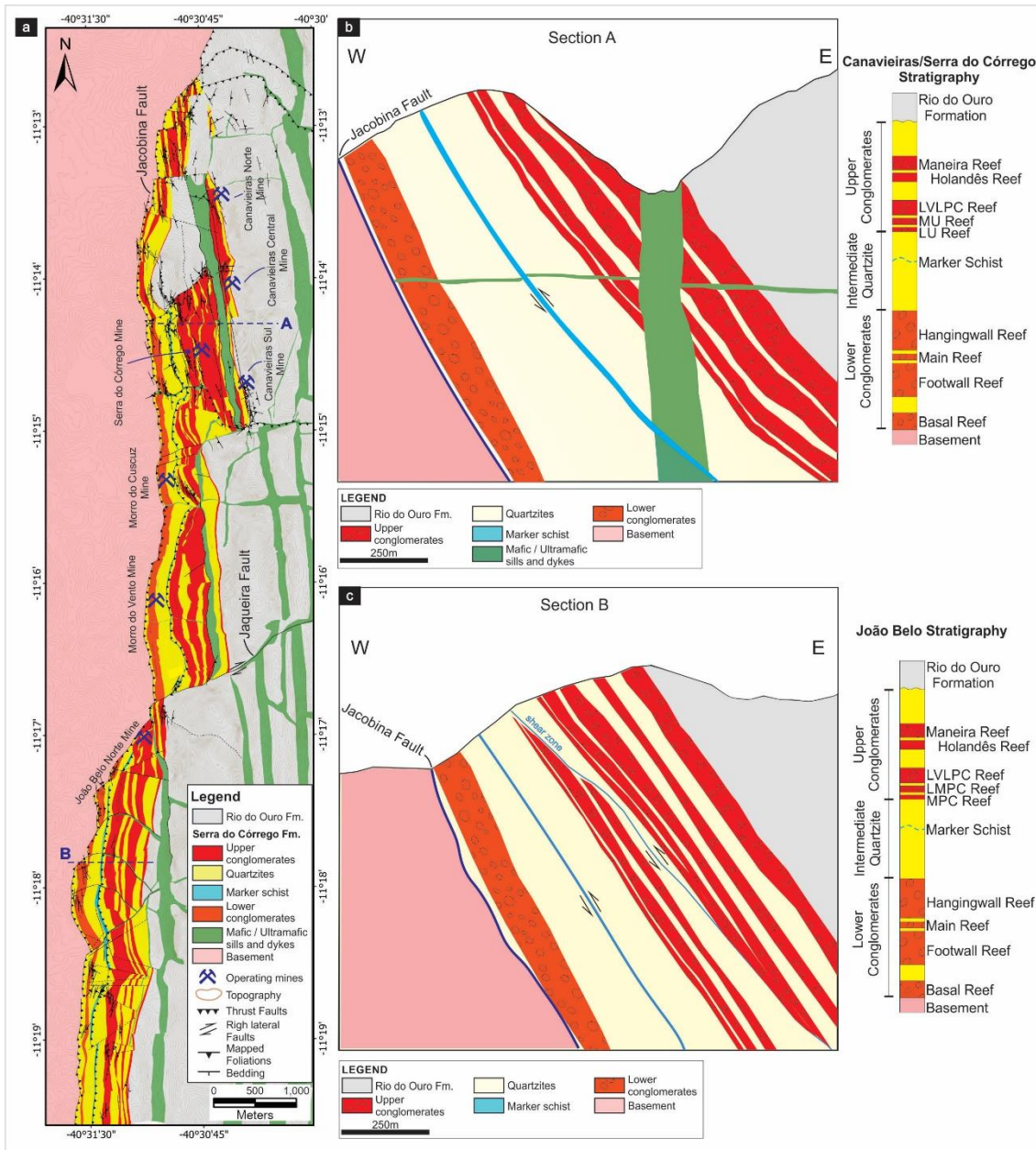


Fig. 5. (a) Geological map of the Jacobina Mining District and location of its mines. (b) Schematic section showing the stratigraphy and geometry of the units constituting the Serra do Córrego Formation in the Canaveiras and Serra do Córrego mines. (c) Schematic section showing the stratigraphy and geometry of the units constituting the Serra do Córrego Formation in the João Belo mine.

3.3. Materials and methods

3.3.1 Field works and sampling

Fieldwork began at the surface, with the execution of regional profiles at a scale of 1:25,000, transverse to the structuring of the Jacobina Range, aiming to collect structural elements, perform kinematic analysis, and understand the regional structural framework. Underground, the work focused on specific points in the underground galleries of the Canavieiras and João Belo mines, considered, in a previous analysis based on channel sampling and drill core assays, to be representative of high-grade mineralized zones and barren zones. Lithological information, structural data, and oriented samples were collected to allow comparing the textural aspects present in the high-grade zones with those existing in low-grade or barren zones. In this phase, 17 points were mapped, with 11 in the Canavieiras mine and 6 in the João Belo Norte mine, where 28 samples considered representative of the mapped points were collected. In total, 27 polished thin sections were prepared to study the microscopic characteristics of the samples obtained underground. Four samples were selected for X-ray microtomography testing, of which two were subjected to the test.

These activities were conducted in two specific campaigns for sample and structural data collection, complemented by systematic geological-structural mapping at a scale of 1:5,000 of targets and mines during the author's routine work as part of the exploration team of the Jacobina Mining District. The methodology used was typical for metamorphic terrains and involved the measurement of planar and linear structural elements (McClay, 1987), description and kinematic analysis of structures, lithological descriptions, preparation of geological profiles in various directions, collection of oriented samples, and documentation of observations through drawings and photographs.

3.3.2 Geochemistry

The samples collected underground from the high, medium, and low-grade zones were subjected to whole-rock geochemical analysis and fire assay at the commercial laboratory ALS, Vespasiano unit, Minas Gerais, Brazil. The concentrations of major elements and base metals were determined by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES), while minor elements and rare earth elements were quantified by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The determination of gold content was performed using fire assay fusion and quantification by Atomic Absorption Spectrometry (AAS) for samples with gold concentrations of up

to 10 ppm. For samples with concentrations higher than 10 ppm, gravimetric analysis was conducted for quantification.

3.3.3 Petrography

With the underground-collected samples, 27 polished thin sections were prepared, including oriented samples for subsequent petrographic and microtectonic analysis. Additionally, analyses were conducted using a scanning electron microscope (SEM) to recognize textural patterns and microstructures. All equipment used is located at the University of Brasília facilities.

3.3.4 X-Ray Computed Microtomography (Micro-CT)

Among the subsurface-collected samples, two were selected for X-Ray Computed Micromography (Micro-CT) testing. This method is based on the attenuation, by absorption or scattering of X-ray beams promoted by minerals present in the samples. This attenuation is generally determined by the energy of the X-ray beams and the density or atomic number of the imaged compounds (Kyle and Ketcham, 2015). Data acquisition is done in two-dimensional slices, generating grayscale values corresponding to the attenuation coefficients of each material traversed by the beam in a specific slice. Hundreds of beams are then fired against the sample from various different positions, generating a large number of slices, which, in the data processing stage, are reconstructed to generate the three-dimensional visualization of the sample and its constituents, segregated by their attenuation coefficient and, indirectly, by their density.

The primary product of scanning with 8-bit resolution is a histogram representing the attenuation coefficients of the materials present in the imaged sample translated into digital numbers constituting a grayscale scale (0 to 255), presented in a frequency versus digital numbers graph of all pixels generated in the analysis, allowing the segregation of mineral phases with similar digital numbers and, consequently, attenuation coefficients using the inflections of the histogram curve.

The choice of samples for this analysis was mainly based on the balance between matrix and pebble quantity, enabling the evaluation of three-dimensional textural framework, the relationship and disposition of sulfides against matrix and gold, and the occurrence forms of the metal in zones of different grades. One limiting factor for micro-CT is the size and shape of the objects to be tested, as they must fit, respectively, into the available space in the equipment's acquisition chamber and into the cylindrical format of

the scanning field (Kyle and Ketcham, 2015). Therefore, the samples subjected to this method were sawed and polished to reach maximum diameter and height of one inch.

In this work, the microtomography images and data were obtained using a SkyScan 1172 microtomograph from the manufacturer Bruker. The acquisition parameters were source voltage of 100kV, source current of 100 μ A, Cu+Al filter, acquisition at 360° with rotation stages of 0.3°. Data processing was performed using the NRECON and CTVOL software, both provided by the equipment manufacturer. All analyses were conducted at the Rock Physical Properties Laboratory, University of Brasília.

3.3.5 Structural Analysis

During fieldwork, both on the surface and underground, planar and linear structural data were collected for kinematic analysis of the observed structures and interpretation of the regional geotectonic evolution and Jacobina mines. Additionally, data available in the structural database generated by the mine geology team active in the Jacobina Mining District were used to understand the geometry of the bodies and correlate them with the structures collected in this research.

Products such as stereograms and paleotensor analysis using the Faultkin 8 software (Marret and Allmendinger, 1990; Allmendinger et al., 2012) were then generated. Subsequently, the individualization of structural domains was carried out, based mainly on the observed geometric differences for the metaconglomerate bodies in the district mines, aiming to understand the architecture of the belt.

The structural analysis conducted in this study was purely qualitative, restricted to descriptive and kinematic analysis of the structural elements. In this context, groups of genetically and temporally related structures were individualized, characterizing a specific phase of deformation (Turnes and Weiss, 1963). The relative age of the structures was established based on classical criteria of cutting and superposition of structures, stress fields in which these structures were formed, and crustal formation level.

3.3.6 Modelling

The data collected during fieldwork, combined with geological, structural, and grade data available in the company's database, were used to develop geological-structural models and model high-grade zones, allowing for the evaluation of the existence of high-grade corridors and their correlations with structures and host rocks,

enabling an understanding of the deposit architecture and its influence on ore concentration. The software LeapFrog Geo was used for the elaboration of the aforementioned models.

Initially, an interpolation of channel sample grades from all mines in the Jacobina Mining District was generated using the company's database, which contains a total of 214,212 samples. This was done in LeapFrog Geo using the Radial Basis Function (RBF) interpolation tool with a linear interpolator, without applying trend trends, and removing samples without results. Capping values were also not used. The interpolation result was subdivided into eight grade intervals, with colors assigned to each interval used to identify low, medium, and high-grade zones in mine galleries triangulations.

Individual litho-structural models of the Canavieiras, Morro do Vento, and João Belo mines were also produced, based on planar data from systematic gallery mappings by the Jacobina Mine Geology team, which currently comprises 45,191 structures, including faults, foliations, veins, breccias, dikes, and shear zones, and on the 328 planar and linear data collected during this research. Only structures considered significant for interpreting the controlling factors of mineralization, especially those visibly associated with high-grade zones, were included.

In addition to the mine models, a regional litho-structural model was produced based on data collected in the regional profiles of this work combined with the database of mapped points by exploration teams in Jacobina, consisting of 8766 points. Data included lithological and structural information, as well as remote sensing using radar (SRTM) and satellite images (CBERS 4a), associated with magnetic and radiometric airborne geophysical survey data, whose acquisition parameters are described in Table 1.

Table 1. Data and parameters applied in the aerogeophysical surveys conducted in the Jacobina Mining District region.

Airborn Survey	Domain	Company	Year	Terrain Clearance (m)	Line Spacing (m)	Line direction	Tie-Line Spacing (m)	Tie-Line Direction
Senhor do Bomfim	Public	CBPM	2001	100	500	E-W	5000	N-S
Jacobina	Private	Desert Sun Mining	1996	100	500	E-W	5000	N-S

The main regional lineaments were delineated using SRTM images with a spatial resolution of 15m, CBERS 4a images with a spatial resolution of 2m, and a derivative tilt image of the magnetic data obtained from aerogeophysical surveys. The result of the Thorium (Th) channel, obtained from collected radiometric data, was used to define the boundaries of the Jacobina basin and its contact with the basement through the Jacobina fault system to the West and the Pindobaçu fault system to the East.

Additionally, renderings of maximum intensity projections of channel sample grades from underground mines were utilized to visualize geometric patterns and control high-grade zones. Renderings of midpoint projections of lithological intervals described in drill core samples were also employed to visualize geometric patterns of metasedimentary bodies in different mines within the Jacobina Mining District.

3.4 Results

3.4.1 Structural Analysis

The intricate structural framework found in the Jacobina Mining District results from the complex deformational history. In this research, groups of genetically related structures were identified, representing the tectonic evolution of the region, which influenced the geometry of the mineralized bodies (Fig. 6). In this context, four deformational phases of great significance were identified, described as follows, beginning with a setting of extensional tectonics and subsequent deposition of sediments forming the Jacobina Group, subsequently affected by compressive and transpressive events resulting from progressive deformation promoted by the Paleoproterozoic Orogeny, and finally by an extensional event, likely representative of the orogen's collapse phase.

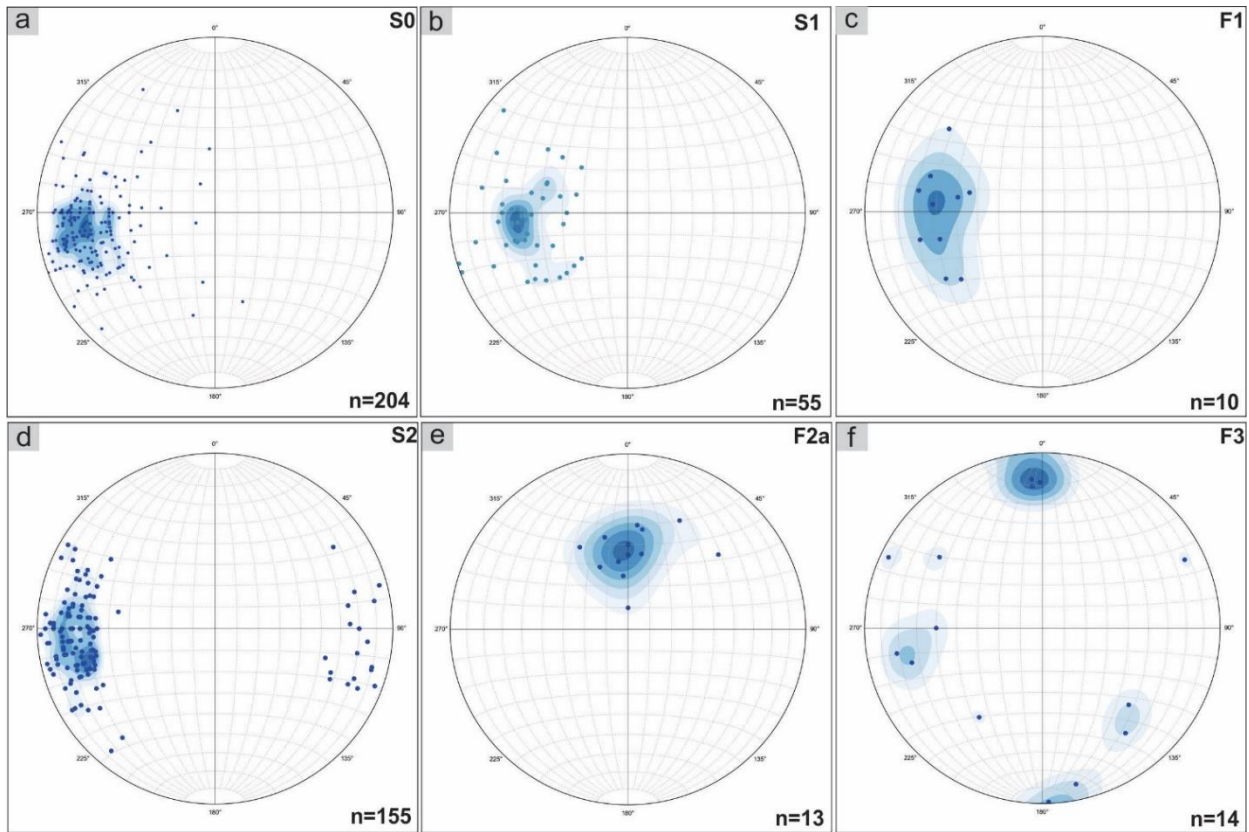


Fig. 6. (a) Stereogram of the poles of sedimentary bedding (S0); (b) Stereogram of the poles of foliation S1; (c) Stereogram showing the attitude of thrust faults F1; (d) Stereogram of the poles of foliation S2; (e) Stereogram of representative frontal ramp thrust faults F2a dipping to the North; (f) Stereograms of normal faults nucleated under extensional tectonics.

Extensional event - sin-depositional

During the extensional event of basin opening and deposition of sedimentary units, primary structures and syn-depositional faults were generated, which controlled the original framework and also the current architecture of the Jacobina Mining District. The remaining primary sedimentary structures in the study area are mainly represented by sedimentary bedding (S0) (Fig. 6a,7a), characterized by intercalations of metaconglomerate and quartzitic levels, as well as planar and cross-bedded stratifications, and less commonly, asymmetric ripples indicating eastward direction in the quartzites of the Serra do Córrego Formation. East-west-directed growth faults (Fig. 7b) were observed in only two of the outcrops visited. These structures were likely obliterated during the tectonic inversion of the basin.

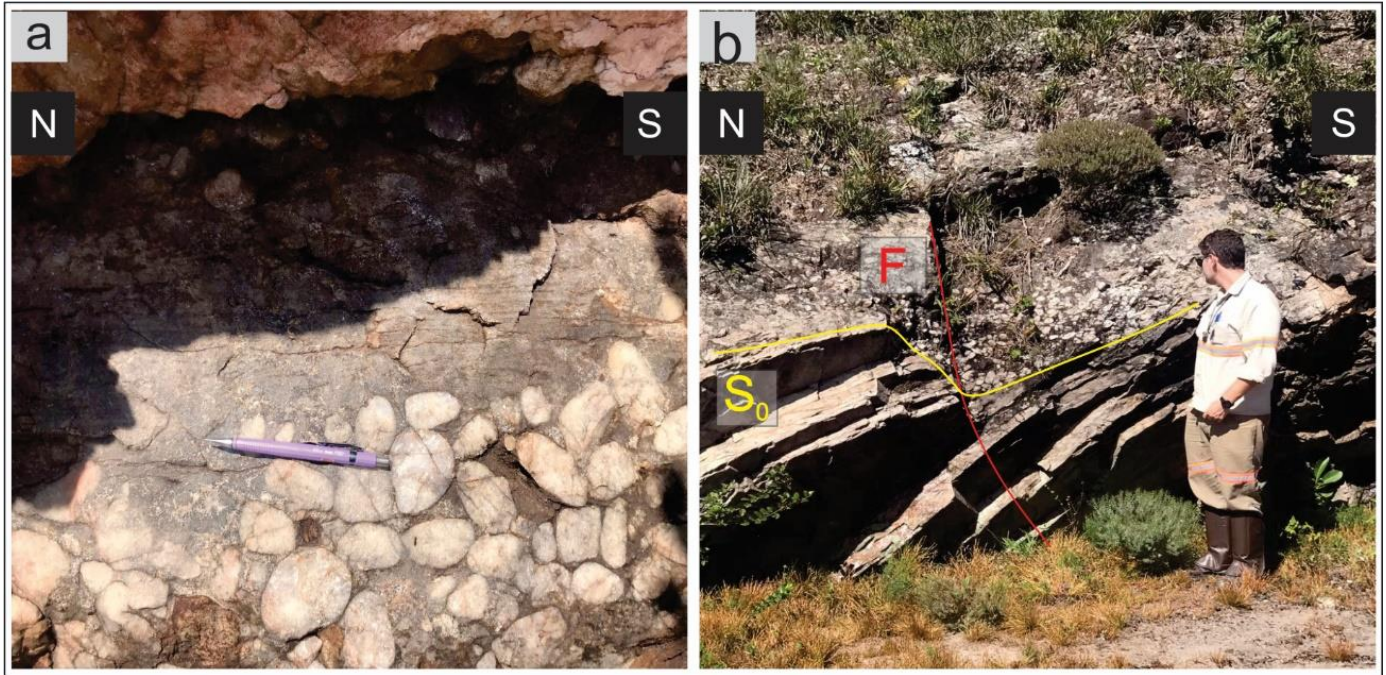


Fig. 7. (a) Sedimentary bedding marked by intercalations of metaconglomerate and quartzite levels ($S_0 = 068^\circ/64^\circ$) in outcrop of the Serra do Córrego Formation, in the João Belo region; (b) Growth fault F_0 ($06^\circ/88^\circ$) in metaconglomerates of the Serra do Córrego Formation, mapped in a mining area in the João Belo region.

Compressive event

The compressive event, related to the inversion of the basin during the Paleoproterozoic orogeny, was subdivided into two distinct phases, with the first phase characterized by frontal compressive tectonics, followed by a phase of transpressive tectonics, in order to facilitate the understanding of the structures generated during this event, despite the progressive nature attributed to the deformation in it.

Frontal compressive phase (D_1)

In this phase of frontal compressive tectonics, developed at ductile to ductile-brittle crustal levels, the main regional foliation, here referred to as S_1 , was formed, with an approximate N-S direction and dip ranging between 40° and 70° to the east. The current configuration of the metasedimentary layers in elongated tabular bodies tectonically imbricated, with an average attitude of $090^\circ/60^\circ$, is also a result of the dominant compressive efforts in this phase. Associated with this phase are reverse faults and shear zones with medium to high angles (F_1) whose planes contain mineral stretching lineations (Lx_1) down dip, and kinematic indicators denoting frontal movement with vergence to the west. At a regional scale, the Jacobina Faults, marking the western boundary of the Jacobina basin with the Gavião Block, and the Pindobaçu Fault,

delimiting the basin to the east, stand out as representatives of this phase, along with the Maravilha Fault system, located in the central portion of the Serra de Jacobina.

In rheological favorable lithologies, such as foliated schists and quartzites, asymmetric closed folds with approximately N-S sub-horizontal axes are observed, denoting vergence to the west. These folds are best observed in sheared quartzites, where the S1 foliation is well marked. It is also observed, in regions where there are lithological intercalations of metaconglomerates and quartzites, that the foldings generated in this phase affect the sedimentary bedding S0, culminating in the parallelism of S0 and foliation S1. The flanks of the folds generated in this phase are generally sub-parallel to foliation S1, which can make it difficult to visualize these folds on an outcrop scale.

Concordant to subconcordant shear zones with the sedimentary bedding also compose the structural framework generated during this phase. These shear zones are continuous and marked by centimeter to meter-scale intensely sheared quartz schist layers, such as the Basal Schist observed at the contact of the Serra do Córrego Formation with the basement, and the Guide Schist, present in the upper third of the intermediate quartzite layer. These structures represent zones of high strain, where the highest intensity of deformation strongly impacted the geometry of the metaconglomerate bodies, including stratigraphic duplications.

Transpressive phase (D₂)

The subvertical foliation S2, with a direction varying between NNW and NNE, is the most representative structure of phase D2. This phase, whose kinematic indicators point to a transpressive tectonics, developed at a ductile to ductile-brittle crustal level and generated mylonitic foliation (S2) that truncates foliation S1. On the planes of foliation S2, there are mineral stretching lineations (Lx2), indicative of directional movement, and striae (Le2), which are sub-horizontal to oblique. The kinematic indicators present in these zones, such as S-C foliations, indicate predominantly sinistral regional kinematics. Locally, kinematic indicators denoting dextral movement for faults originated in this phase are found.

During transpression, mainly in the northern portion of the Jacobina Mining District, where drill hole data indicate the existence of basement highs, thrust ramps with NNW vergence were nucleated, marked by faults (F2a) with high-rake striations and steps indicating reverse to reverse-dextral kinematics with vergence to the north. Near these

thrust faults, a spaced foliation (S2a) developed, whose planes dip between 30° and 45° to the south. The nucleation of these thrusts appears to have been responsible for the arching of the metasediments and the consequent formation of large-amplitude open folds, with E-W axes dipping between 30° and 50° to the east, represented mainly by the geometry of the metaconglomerates in the Canavieiras Sul mine. Other examples of this type of structure were visualized in the geological models of the central portion of the Serra do Córrego mine and in the extreme north of the Canavieiras Norte mine. Due to the large amplitude of these folds, their visualization on an outcrop scale is quite rare.

This phase is also attributed to the nucleation of shear zones and directional faults F2b, with an approximate ENE-WSW and ESE-WNW direction, with dextral kinematics indicated by mineral stretching lineations (Lx2b) and S-C structures (Fig. 8e). These shear zones are marked by a subvertical penetrative mylonitic foliation S2b, observed in quartz schists outcropping in the deep valleys of the same direction, representing a late-D2 phase due to the fact that they truncate foliations S1 and S2, generating discontinuities observed at the deposit scale. In the Jacobina Mining District, these structures are highly relevant due to their notable offset, which promotes the separation of the João Belo Norte and Morro do Vento Sul Mines.

Extensional event (D₃)

In this predominantly extensional tectonic phase, developed at a brittle crustal level, normal faults (F3) were nucleated, marked by high-angle striations (Le3) with throws ranging from down dip to oblique. In some outcrops, the overlap of Le3 striations with mineral stretching lineations Lx1 and Lx2 is observed, indicating the reactivation of thrust faults and strike-slip faults generated in previous deformational phases, such as normal faults during orogenic collapse, a fact corroborated by the various directions observed for these structures. The reactivation of structures formed in D₁ and D₂ as normal faults promotes the movement of metaconglomerates as large blocks, generating significant structural discontinuities along the mineralized zones of the district.

The extensional phase is also responsible for the generation of breccias with varying attitudes, appearing subparallel or truncating the metasedimentary bodies, with dimensions ranging from centimeters to decameters. In general, the breccias exhibit very angular clasts of various sizes, with their interstices commonly filled with quartz and hematite. These structures, which appear throughout the Mining District, are generally barren, and when they cut across the metaconglomerates, they can represent important

zones of low economic viability, as is the case with the Brecha Sul in the Morro do Vento Sul mine.

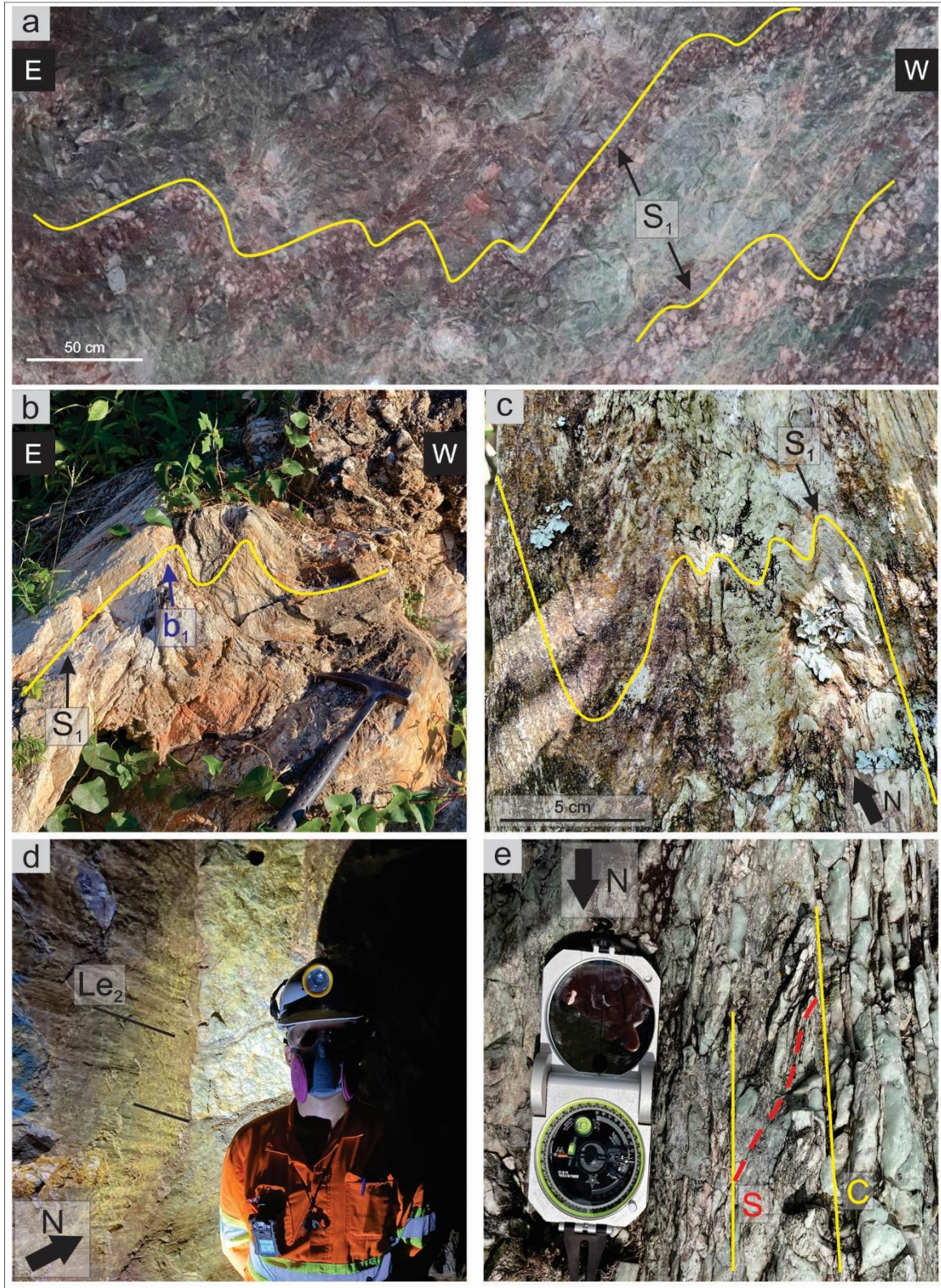


Fig. 8. (a) S_0/S_1 displaying asymmetric folds with approximately N-S axes, in development face of the underground mine of Canavieiras Sul; (b) S_1 foliation displaying asymmetric fold with approximately N-S axis ($b_1 = 354^\circ/12^\circ$) in outcrop of the Serra do Córrego Formation; (c) S_1 foliation exhibiting closed folds with sub-parallel limbs and

approximately N-S axis ($178^{\circ}/30^{\circ}$); (d) F2 fault with approximately N-S direction ($265^{\circ}/75^{\circ}$) and well-defined sub-horizontal slickensides ($Le2= 355^{\circ}/04^{\circ}$), with steps indicating dextral kinematics; (e) Quartzite outcrop showing S-C foliation indicating left lateral movement

3.4.2 Structural Domains

The three-dimensional analysis of the geometry of the metasedimentary bodies in the mines of the Jacobina District allowed the individualization of three structural domains (Fig. 09), separated with the aim of facilitating the understanding of the geometric and structural framework and the controlling factors of high-grade shoots in each of the domains.

The Northern Domain comprises the prolific mines of Canavieiras Sul, Canavieiras Central, and Canavieiras Norte. In turn, the Morro Vento and Morro do Cuscuz mines integrate the Central Domain. Finally, the João Belo Norte mine is the sole member of the Southern Domain, with an average plane of the mapped foliations S_n .

Regarding the mapped faults, there is a great similarity in the behavior of these structures in the Northern and Central domains, with a predominance of four families of directions: NNW-SSE dipping to NE, NNW-SSE dipping to SW, ENE-WNW dipping to SE, and ENE-WNW dipping to NW. However, in the Southern Domain, there is a slight discrepancy due to the occurrence of a family of WNW-ESSE faults dipping to SW, in addition to the NNW-SSE and ENE-WNW families. The other structures in the databases, such as veins, shear zones, and breccias, did not show significant discrepancies between the domains to be used as separation criteria.

The observed structural domains are separated by large-scale structures, with the Central and Southern domains separated by an important E-W fault, named the Jaqueira Fault (Fig. 09). In turn, the Northern domain is the only one where mining operations occur in the block to the east of the N-S Valley that separates the mines of the district, with no direct contact with the basement. The other domains are located on the western boundary of the district, in tectonic contact with the Gavião block, representing the basement in the area.

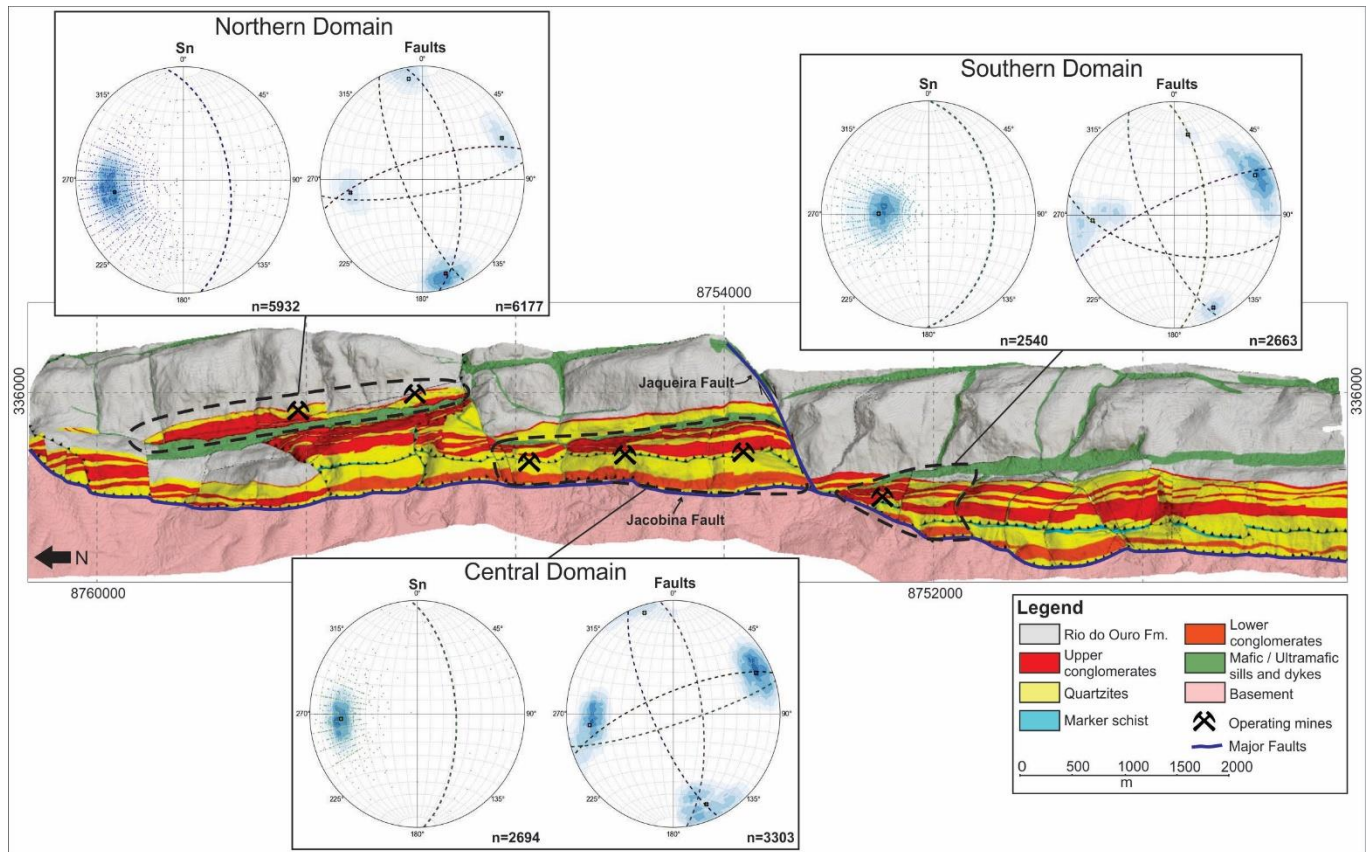


Fig. 9. Map representation of the northern, central, and southern structural domains of the Jacobina Mining District with stereographic diagrams of the main foliation and faults in the different domains.

Northern Domain

Analyzing the attitude of the mean plane obtained for the measurements of foliations Sn in isolation in the Northern Domain, no clear distinction is observed between this domain and the Central and Southern Domains. However, the three-dimensional geological visualization of the mines in the Northern Domain denotes the existence of open folds with an approximately E-W axis (Fig. 10a), a fact corroborated by the variation in the directions of the foliations measured in galleries, better evidenced in the Canavieiras Sul mine (Fig. 10b). These open foldings can also be identified by the variation in the attitude of the foliations Sn in the Canavieiras Sul, Central, and Norte mines, as observed in the stereogram of the Sn foliation (Fig. 10c), in which the mean planes of the pole groupings in the third and fourth quadrants agree with the existence of open folds. It is worth noting that, in the Canavieiras Sul mine, the dip of the foliations, and consequently, the axes of the folds in question, is slightly lower than in the Canavieiras Central and Norte mines.

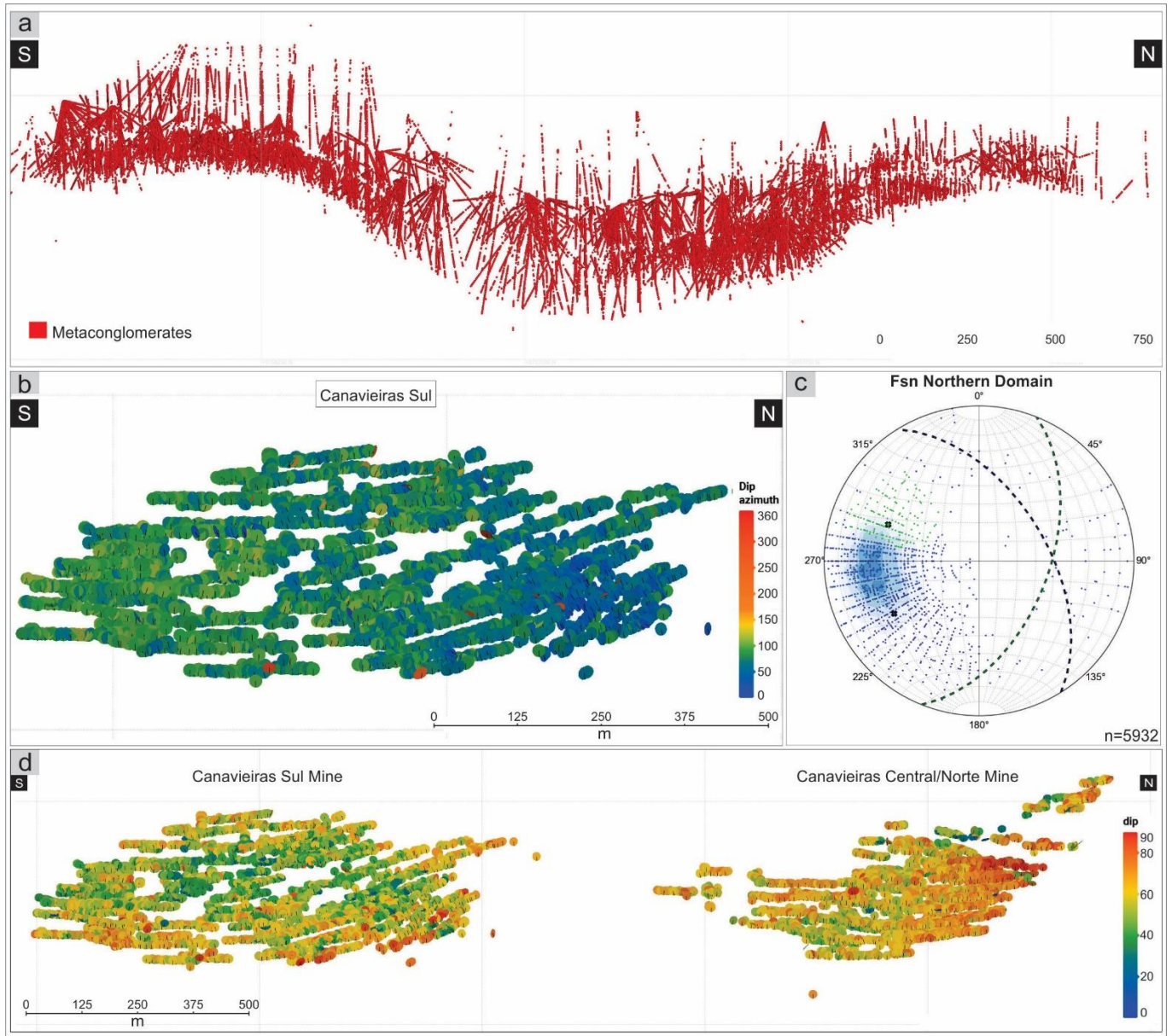


Fig. 10. (a) Maximum intensity projection of the interval midpoints described, in drillholes, as metaconglomerates, in the mines of the Northern Domain, with an orthogonal view to the dip of the layers. (viewed towards W, plunge -30°); (b) Representative disks of Sn foliation measurements obtained in systematic mapping of galleries in Canaveiras Sul mine showing their dip azimuth; (c) Stereogram of Sn foliations collected in development fronts in the underground mines of Canaveiras Sul, Canaveiras Central, and Canaveiras Norte with segregation of poles by quadrant. (d) Three-dimensional modeling of Sn foliations obtained in systematic mapping of galleries in Canaveiras Sul, Canaveiras Central, and Canaveiras Norte mines. Disks represent dip measurements of the foliations (viewed towards W, plunge +30°).

In addition to changes in the direction of foliations, the mines comprising the Northern Domain also exhibit variations in the dip of the layers, with an average dip of 53° to the east in the Canaveiras Sul mine and 62° to the east in the Canaveiras Central and Canaveiras Norte mines (Fig. 10d).

Central Domain

The Central Domain features predominantly tabular metaconglomerate bodies oriented in a north-south direction (Fig. 11a) with dips ranging from 55° to 90° to the east, the steepest among the three domains (Fig. 11b, c), with few variations in the directions of foliation S_n , both for the Morro do Vento and Morro do Cuscuz mines (Fig. 11b).

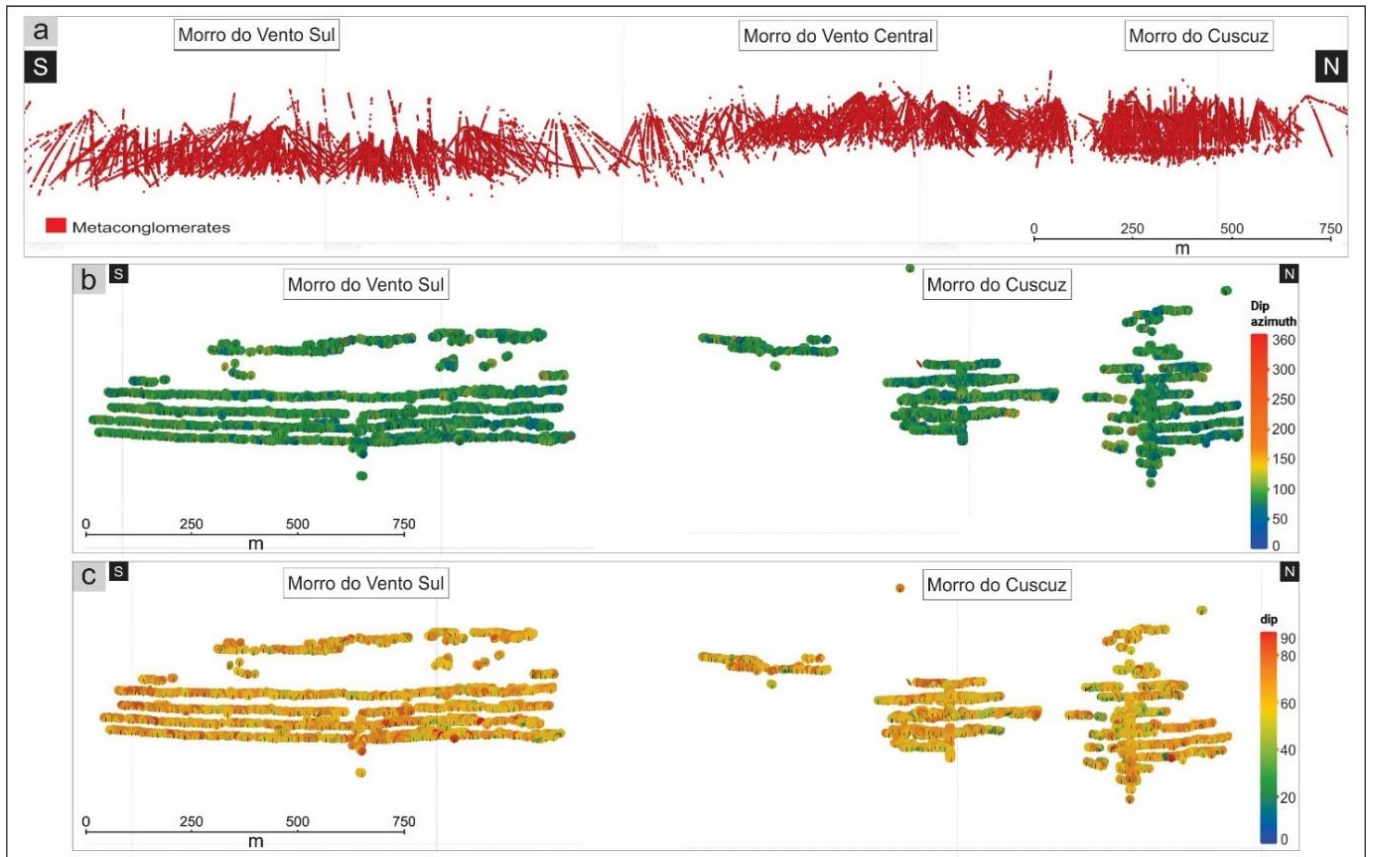


Fig. 11. (a) Maximum intensity projection of the interval midpoints described as metaconglomerates in drillholes, in the mines of the Central Domain, with an orthogonal view to the dip of the layers. (viewed towards W, plunge -65°); (b) Representative disks of the direction measurements of foliations S_n obtained in systematic mapping of galleries in Morro do Vento and Morro do Cuscuz mines, showing their dip azimuth (Viewed towards W); (c) Representative disks of dip measurements of foliations obtained in systematic mapping of galleries in Morro do Vento Sul and Morro do Cuscuz mines (Viewed towards W).

It is important to emphasize that the Central Domain concentrates its production on the lower metaconglomerates of the Serra do Córrego Formation, distinguishing it from the others, which produce from the upper metaconglomerates. Thus, the Morro do Vento and Morro do Cuscuz mines are very close to or in direct contact with the basal detachment zone and the basement, with their geometry strongly controlled by the latter.

Southern Domain

In the Southern Domain, exclusively composed of the João Belo Norte mine, the metaconglomerates are tabular, with a N-S orientation, and dips ranging between 80° and 05° to the East, giving this domain a unique sigmoid geometry (Fig. 12a, b). The variations in dips are associated with the presence of three important shear zones (Fig. 12c) marked by fuchsite and sericite-quartz schists. This system of shear zones affects the stratigraphy, leading to the duplication of the LVLPC, LMPC, and MPC Reefs in a fault system with apparent normal anatomy, which not only duplicates the stratigraphy but also displaces metasedimentary bodies as blocks (Fig. 12c).

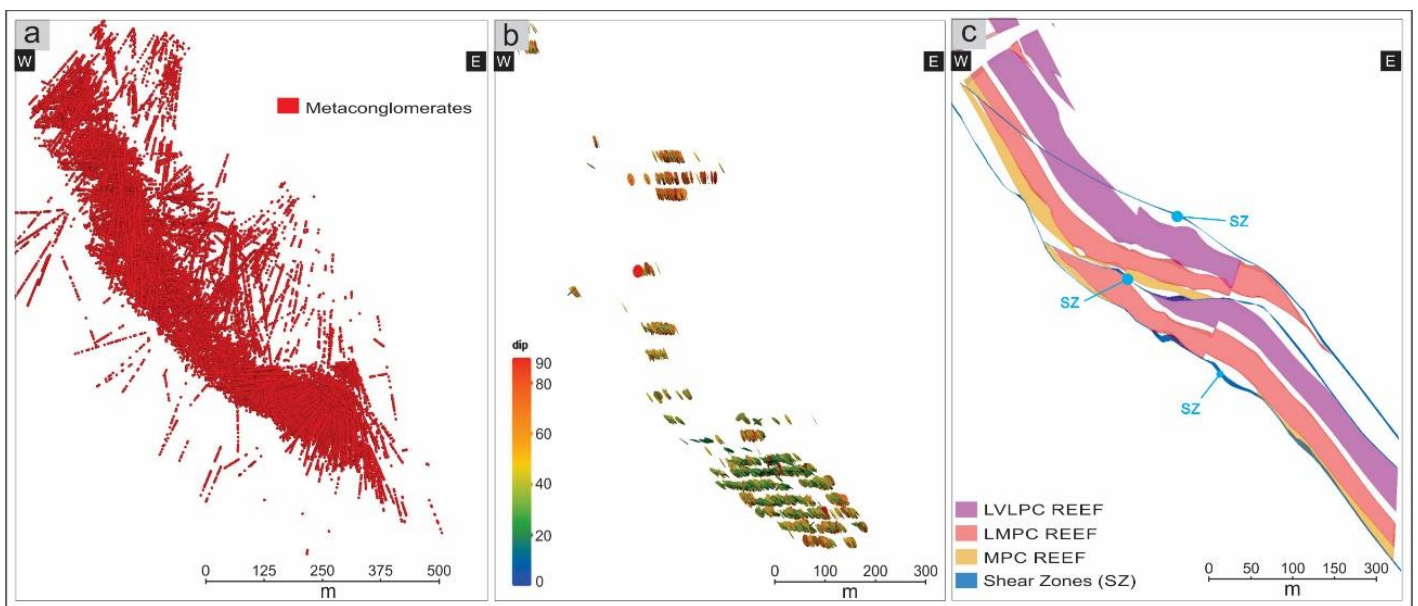


Fig. 12. (a) Maximum intensity projection of the interval midpoints described as metaconglomerates in drillholes, in the Southern Domain, with a view perpendicular to the dip of the layers (viewed towards N); (b) Representative disks of the dip measurements of foliations S_n obtained in systematic mapping of galleries in João Belo Norte mine (viewed towards N); (c) Section of the geological-structural model of João Belo Norte mine (Viewed towards N) showing layer duplication and modelled shear zones.

3.4.3 Gold mineralization in the structural domains

Auriferous mineralization presents particularities in the different structural domains in terms of average grade, structural control, and geometry of high-grade corridors. Analysis of the drill hole assay database (Table 2) reveals that the Northern Domain has the highest average grade among the three, followed by the Central and Southern domains, which exhibit very similar averages. Concerning the groups of very low to moderate grades (1 to 10 g/t Au), there is little difference among the three domains, with similar percentages of samples falling within this range relative to the total number

of samples. However, for the high to very high-grade ranges (10-100 g/t Au), the number of samples from the Northern Domain is two to three times greater than in the other domains, while for extremely high grades (>100 g/t Au), the Northern Domain surpasses the Central and Southern domains by more than six times.

Table 2. Comparative table, by domains, of gold grades obtained in drill holes.

DOMAIN	Average grade (g/t)	Number of samples	%
NORTH	5.17	52537.00	37.23
Grade classes			
1 - Very Low (1-3g/tAu)	1.74	31453.00	22.29
2 - Low (3-5g/tAu)	3.85	9010.00	6.38
3 - Moderate (5-10g/tAu)	7.24	6212.00	4.40
4 - High (10-30g/tAu)	16.27	4746.00	3.36
5 - Very High (30-100g/tAu)	45.85	1034.00	0.73
6 - Extremely High (>100g/tAu)	151.45	82.00	0.06
CENTRAL	3.76	37986.00	26.92
Grade classes			
1 - Very Low (1-3g/tAu)	1.71	25923.00	18.37
2 - Low (3-5g/tAu)	3.82	6069.00	4.30
3 - Moderate (5-10g/tAu)	7.11	3595.00	2.55
4 - High (10-30g/tAu)	15.81	2080.00	1.47
5 - Very High (30-100g/tAu)	46.59	301.00	0.21
6 - Extremely High (>100g/tAu)	155.49	18.00	0.01
SOUTH	3.73	50594.00	35.85
Grade classes			
1 - Very Low (1-3g/tAu)	1.75	32811.00	23.25
2 - Low (3-5g/tAu)	3.83	9328.00	6.61
3 - Moderate (5-10g/tAu)	7.00	5682.00	4.03
4 - High (10-30g/tAu)	15.54	2457.00	1.74
5 - Very High (30-100g/tAu)	44.36	300.00	0.21
6 - Extremely High (>100g/tAu)	265.29	16.00	0.01
Total		141117.00	

Despite economically viable gold mineralization being restricted to the metaconglomerates of the Serra do Córrego Formation, the modeling of structures collected in underground galleries associated with interpolations of channel sample grades highlights the intrinsic relationship of tectonic structures with the control of high-grade mineralized zones (Fig. 13a). In general, foliations S1 and S2 and faults F1 and F2 are correlated with grades along their entire NW-SE strike, generating high-grade zones with trends subparallel to these structures, disagreeing with the direction of the metaconglomerate bodies, as highlighted in the northern portion of Figure 15a, which illustrates the observation, in plan view, of the NW-SE trends of mineralization.

The same applies to the João Belo mine in the Southern Domain, where it is observed that different metaconglomerate bodies, with distinct characteristics (grain size, packing, hydrothermal alterations), belonging to the different productive Reefs of the mine (LVLPC, LMPC, and MPC), when intersected by the same N-S trending fault F2, exhibit continuous mineralization along these structures, including at different productive levels of the mine, as highlighted in Figure 15b, which represents an observation of the continuity, in depth, of the mineralization, with emphasis on the high-grade zone present in the northern portion of Figure 15a.

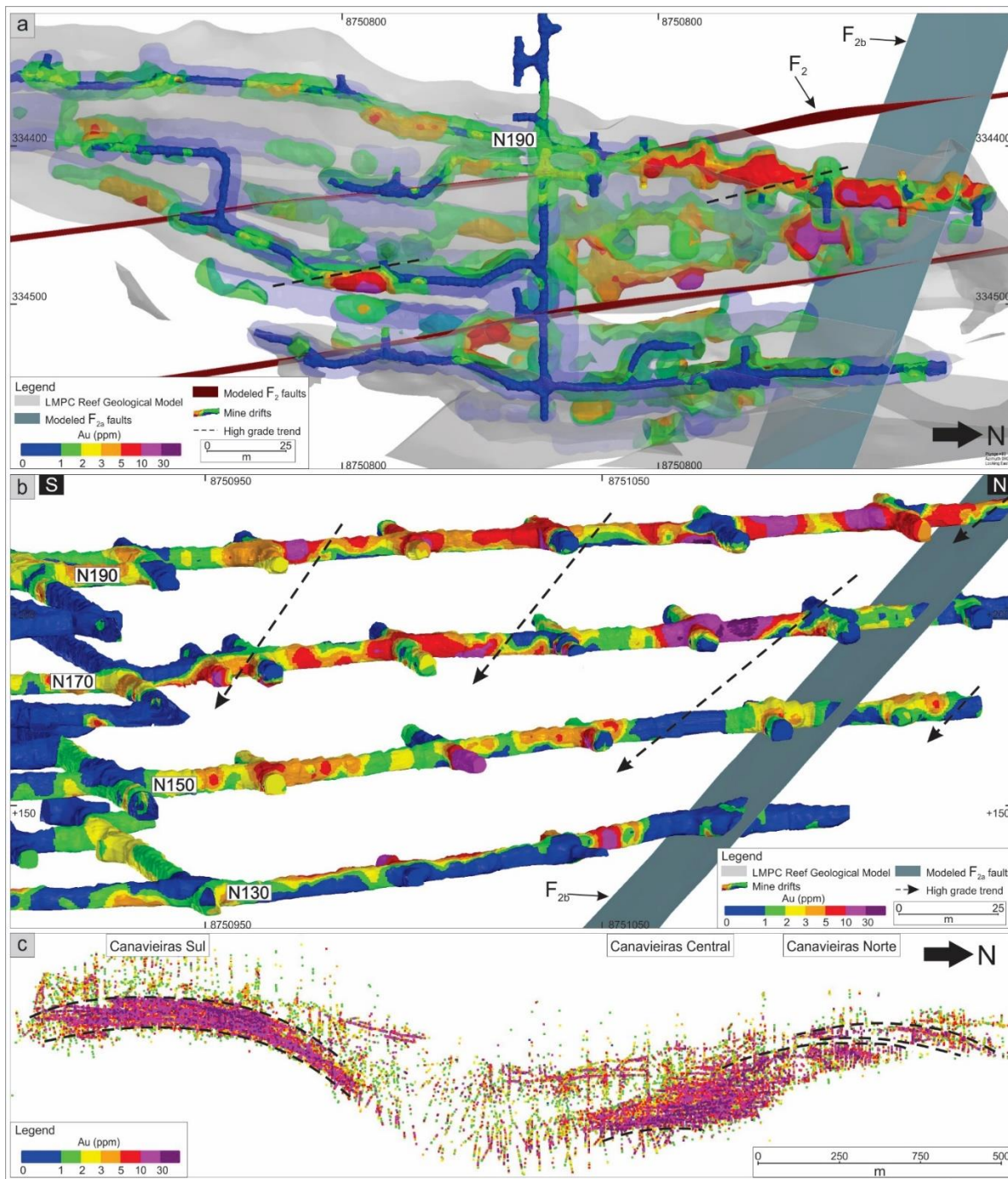


Fig. 13. (a) Three-dimensional visualization, in plan view, depicting the interplay between high-grade interpolations derived from Radial Basis Function analysis of channel samples and the structural features of F2 and F2b in the LMPC Reef at João Belo Norte mine. Dashed lines delineate the trajectory of high-grade zones, which align subparallel to the modeled faults. It's important to note that the modeled fault planes represent a subset of the broader F2 fault group due to limitations in visual representation.; (b) N-S cross-section zooming in on the mineralized zone showcasing the three-dimensional layout of galleries within the underground workings of João Belo mine, color-coded to reflect gold grade values obtained through Radial Basis Function interpolation. Additionally, a representative modeled fault F2b, derived from underground data, is depicted. Arrows accompanied by dashed lines indicate the plunge direction of mineralization, which aligns with the modeled faults and varies between 40° and 60° SE. (c) N-S section view of the maximum intensity projection of gold grades from drill holes and channel samples from mines within the Northern Domain. Dashed lines denote areas with a higher concentration of high-grade samples.

In the Canavieiras Sul mine, belonging to the Northern Domain, based on the interpolation of channel grades overlaid on gallery triangulations developed in the Canavieiras Sul mine, it is possible to notice that the developments made in the northern portion of this mine, which follow the NW-SE fault direction, exhibit greater continuity of high-grade zones than their counterparts in the N-S direction to the south. Similar to the João Belo mine, the structures mapped here also appear mineralized when intersecting different Reefs (Maneira, LVLPC, MU, and LU).

In the mines of the Northern Domain, in addition to the high concentration of ore in structure intersections, the folded geometry of the bodies also appears to concentrate gold in greater quantities near the apical zones of the folds, as denoted by the high frequency of samples with very high grades (>30g/tAu) in the central region of the Canavieiras Sul mine and north of the Canavieiras Central and Canavieiras Norte mines (Fig. 13c), with a decrease in the occurrence of these samples in the sinform geometry portion between the Canavieiras Sul and Central mines.

On the other hand, the structures S2b and F2b, with directions ENE-WSW and ESE-WNW, seem to play an important role in controlling mineralization, as it is at the intersections between them, the metaconglomerates, and the approximately NW-SE structures (S1 and S2), where the occurrence of the highest-grade zones in the Southern and Central Domains is observed, where the geometry of the bodies is essentially tabular. These structures appear to exert a strong influence on the continuity of mineralization at depth, as they produce a high-grade trend with a plunge ranging between 40° and 60° to the SE, subparallel to structures S2b and F2b (Fig. 13b).

3.4.4 High-grade zones characterization

The detailed analysis of drill core samples and underground gallery development fronts has shown that there are no primary or secondary textural and mineralogical characteristics of the metaconglomerates capable of distinguishing high-grade from low-grade zones in the Jacobina Mining District, except for the higher intensity of deformation observed in higher-grade zones. Macroscopic features such as fuchsitic alteration, oxidation, sulfidation, and sedimentary textural characteristics related to pebble sizes, packing, granulometry, and matrix percentage are common to both low-grade and high-grade zones, making the identification of high-grade zones complex at the outcrop scale.

The use of three-dimensional lithological and gold grade models from drill hole data indicates that, in all structural domains, the highest grades are concentrated at the top of the metaconglomerates, near the contact with overlying quartzites, as illustrated in Figure 16, where the colored bars represent gold grade values obtained from drill hole samples.

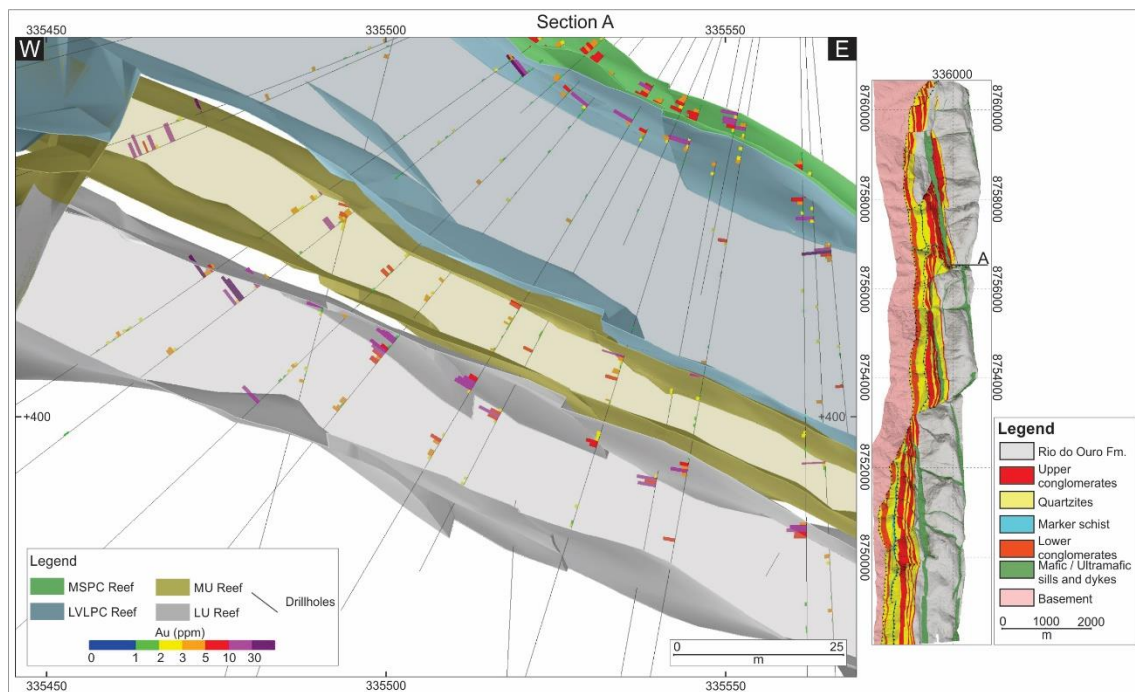


Fig. 14. Three-dimensional model of the metaconglomerate bodies at Canavieiras Sul mine, generated from drill hole data and underground gallery mapping. It's worth noting that samples with the highest grades, collected from drill holes and represented by colored bars, are typically located at the top of the mineralized Reefs. In the image: MSPC Reef in green, LVLPC Reef in light blue, MU Reef in gold, and LU Reef in gray.

In the field and in drill core samples, it is observed that regions of higher grades are generally associated with intensely deformed zones at ductile to ductile-brittle crustal

levels, a fact evidenced by the presence of stretched pebbles and mineral stretching lineations on shear planes. In these zones, there is also intense fracturing of the rock mass, with penetrative cleavages of fractures subparallel to foliations S1, S2, S2a, and S2b, whose planes are occasionally filled with gold (Fig. 15a, b, f). Additionally, in the high-grade zones, gold occurs associated with fault planes F1, F2, and F2b, including in pyrites (Fig. 15d) and disseminated in the matrix (Fig. 15c, e), with the latter two forms of occurrence being more easily observable at a microscopic scale.

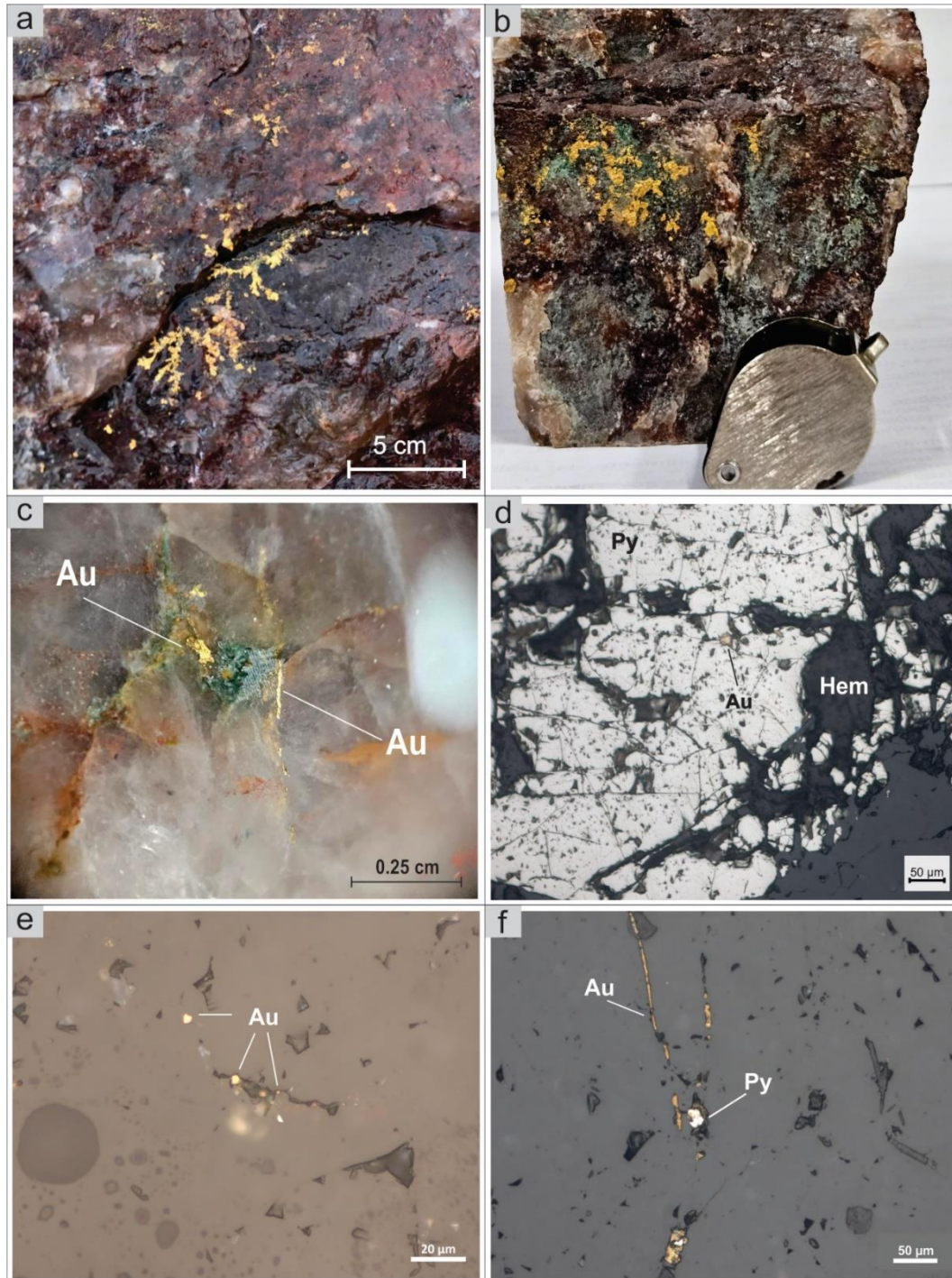


Fig. 15. (a) Dendritic gold on fracture plane in samples collected at level N270 of Morro do Cuscuz mine; (b) Placer gold on fracture plane in sample collected at Canavieiras Central mine; (c) Gold associated with fuchsite in the matrix and filling fractures in core sample (drill hole MVTEX00189); (d) Reflected light photomicrography of gold associated with pyrite (Py) in sample GSR-P14-L1, collected at João Belo mine. (e) Reflected light photomicrography of gold nuggets filling interstices between quartz grains in the matrix, sample GSR-P5-L1; (f) Reflected light photomicrography of gold filling microfractures in sample GSR-5-L.

The study conducted using X-ray Computed Microtomography (Micro-CT) technique was based on the separation of classes with different energy attenuation coefficients in a histogram that reflects density contrasts between mineral phases present in the samples. The samples GSR-P6-L2 (7.94 g/t Au) and GSR-CAC-N130 (36.59 g/t Au) were subjected to this procedure, representing respectively a zone of moderate grade and a zone of very high grade. These samples exhibited distinct textural characteristics and parageneses, where the GSR-P6-L2 sample showed a fuchsitic matrix, euédric to sub-euédric pyrites, moderate oxidation, and no visible gold specks, while the GSR-CAC-N130 sample appeared intensely oxidized, with pyrites strongly altered to hematite and goethite, lacking fuchsite, with gold filling fractures and fault planes.

The prior knowledge obtained from outcrop and microscopic analysis of these samples optimized the evaluation of attenuation curves generated in a two-dimensional digital slice of each sample (Fig. 16a, b), allowing the identification of mineral phases responsible for the peaks observed in the attenuation curves, and the recognition of digital numbers obtained for each mineral class in the histograms generated for the tested samples.

The histogram obtained for sample GSR-P6-L2 allowed the separation of sample constituents into four groups with digital numbers representing ranges of similar attenuation coefficients (Fig. 16a1,2,3). The first group, with digital numbers from 0 to 30, was generally classified as gangue, consisting of quartz, including pebbles, and indistinct micas due to the low density of these minerals. The second group, called Sulfides 1, with digital numbers from 31 to 87, corresponds to the sulfide mineral phase and is predominantly composed of pyrites. The third group, with digital numbers from 88 to 164, was called Sulfides 2, and presents higher attenuation coefficients than the second group, but lower than the fourth group (gold group), possibly representing denser sulfides than pyrite, very small gold inclusions in pyrites elevating their density, or transition pixels generated by the high density contrast between gold and other minerals of very low

density constituting the samples. The last group, with digital numbers between 165 and 255, was classified as the gold group.

The histogram obtained for sample GSR-CAC-N130 also allowed the separation of sample constituents into four groups with digital numbers representing ranges of similar attenuation coefficients (Fig. 16b1,2,3). The first group, also classified as gangue, consists, like in the previous sample, of quartz, including pebbles, and indistinct micas, with digital numbers between 0 and 10. The second group, also called Sulfides 1, with digital numbers from 11 to 35, represents strongly oxidized sulfides, altered to hematite and goethite. The third group, with digital numbers from 36 to 65, was called Sulfides 2, and presents higher attenuation coefficients than the second group, coinciding with the behavior of less altered pyrites observed in the attenuation curve of sample GSR-P6-L2. The last group, with digital numbers between 66 and 255, was classified as the gold group.

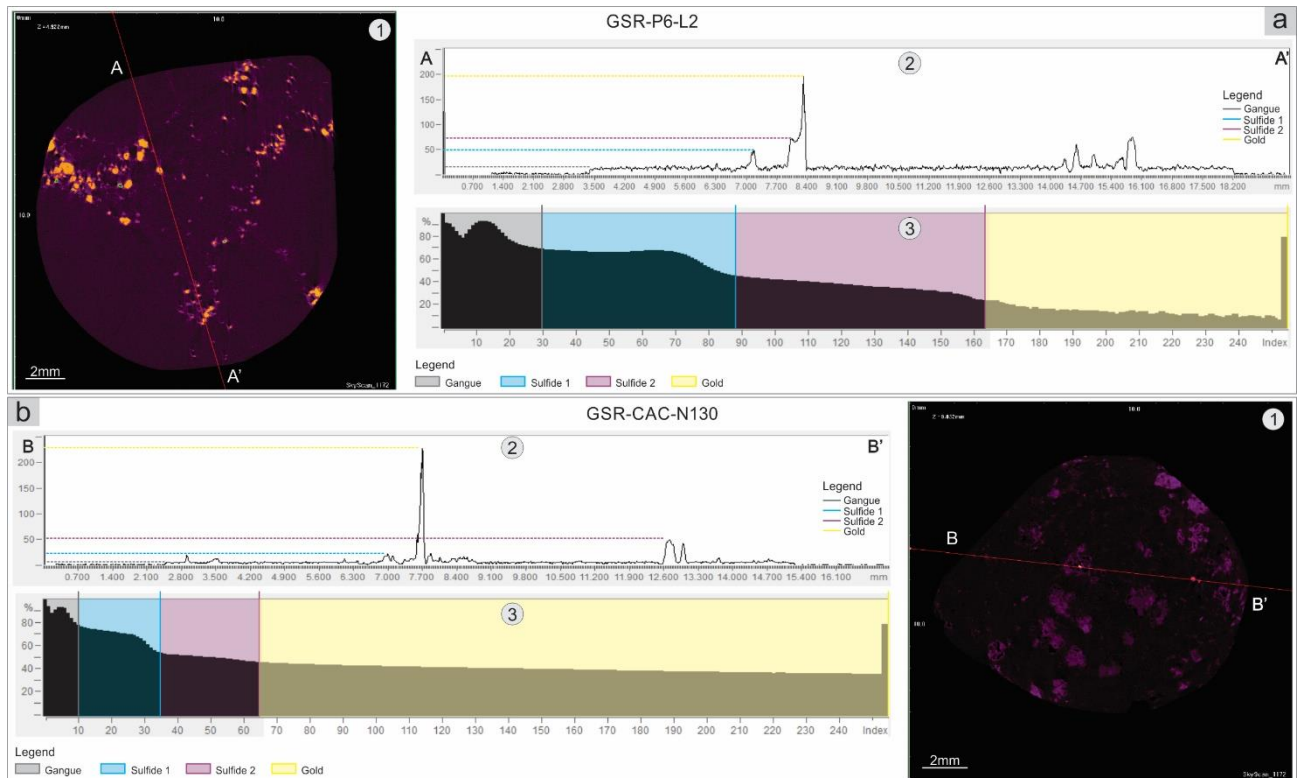


Fig. 16. (a) 1- Two-dimensional slice image of sample GSR-P6-L2, artificially colored, highlighting in yellow the class of Sulfide 1, with attenuation profile A-A' traced over the red line; 2- Attenuation profile A-A' showing the response of the different constituent elements of the sample. Peak heights are directly proportional to the density of the material penetrated by X-ray beams; 3- Digital number histogram used for the segregation of grayscale bands representing each constituent mineral of the sample; (b) 1- Two-dimensional slice image of sample GSR-CAC-N130, artificially colored, highlighting in yellow the class of gold, with attenuation profile B-B' traced over the red line; 2- Attenuation profile B-B' showing the response of the different constituent elements of the sample. Peak heights are directly proportional to the density of the material penetrated by X-ray beams; 3- Digital number histogram used for the segregation of grayscale bands representing each constituent mineral of the sample.

With the mineral phase classes adjusted via histogram, cylindrical regions of interest (ROI) were defined to best represent the textural features and relationships between the constituents of the selected samples. Initially, the resolution obtained for sample GSR-P6-L2 was 4.69 μm , and for sample GSR-CAC-N130, 4.28 μm . However, for the three-dimensional reconstruction of the analyzed volumes, a 2:1 resampling was applied to the images, generating pixels of 9.37 μm and 8.56 μm , respectively, for samples GSR-P6-L2 and GSR-CAC-N130. This loss of resolution is necessary for processing and data analysis purposes.

In sample GSR-P6-L2, the gold is fine and appears free in interstices between quartz grains in the matrix, and within some pyrite grains (Fig. 17a). The pyrite grains classified as Sulfide 1 are sub-euédric to euédric and show little alteration, and these are the carriers of gold associated with sulfides (Fig. 17b). In this sample, the pixels assigned to the Sulfide 2 class appear to be transition pixels generated by the pronounced density contrast between gold and the adjacent gangue, resulting in grayscale tones with digital numbers intermediate between these two components and similar to those of the Sulfide 1 group. Therefore, in this case, it is doubtful to consider that there is a second phase of sulfides with slightly higher density and, consequently, attenuation coefficient than the sulfides constituting the Sulfide 1 group.

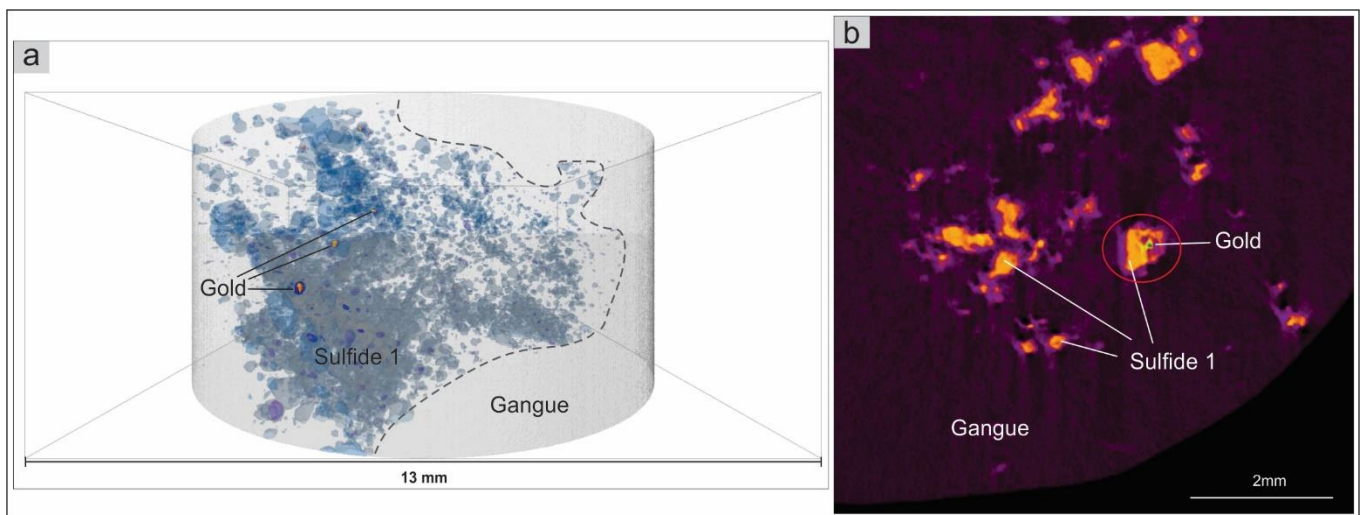


Fig. 17. (a) Three-dimensional reconstruction of sample GSR-P6-L2 showing the relationship between Gangue (gray), Sulfide 1 (blue), and Gold (yellow) groups. Note the fine gold grains associated with sulfides and within the matrix; (b) Two-dimensional slice image of sample GSR-P6-L2, artificially colored to highlight the Sulfide 1 class in yellow and the Gold class in green, with emphasis on a subhedral pyrite grain containing gold within it.

In sample GSR-CAC-N130, most of the gold appears to fill mutually sub-orthogonal fractures, in addition to being disseminated in the matrix and within altered

pyrite grains (Fig. 18a). When filling fractures, the gold is coarse and has a platy shape, similar to what is observed in hand samples (Fig. 18a). Its concentration in the two observed fracture directions is visually discrepant, so that in fracture 1 (Fig. 18b1), the metal appears in greater quantity and in larger grains compared to fracture 2 (Fig. 18b2). It was not possible to determine the orientation of these fractures to associate them with any deformational or mineralizing event. However, the structural and textural aspects observed in the microtomography highlight the importance of remobilization and epigenetic processes in the formation of high-grade corridors. A better 3D visualization of these textural and structural aspects can be accessed in the videos provided in Annex 1.

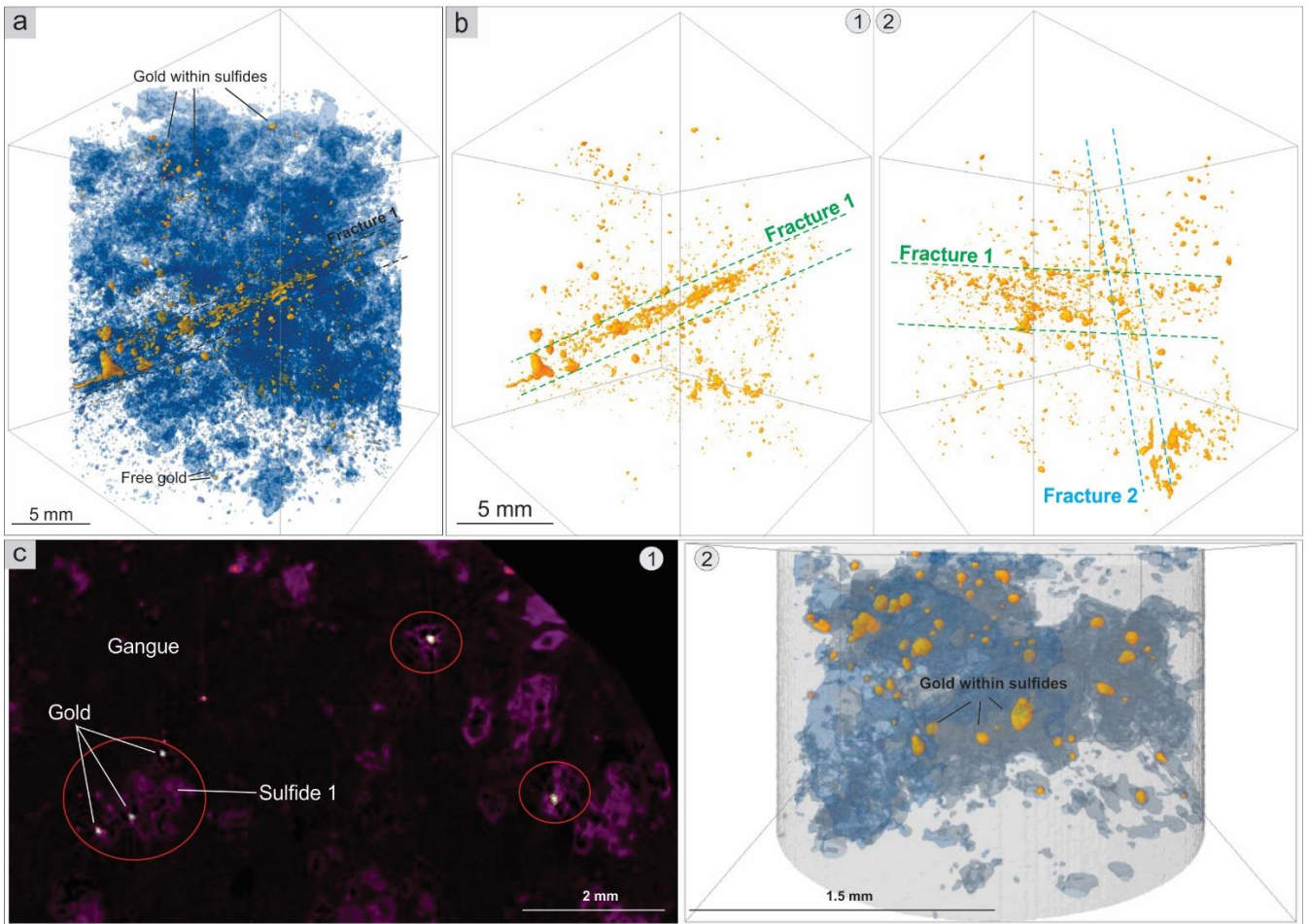


Fig. 18. (a) Three-dimensional reconstruction of sample GSR-CAC-N130 showing the relationship between Sulfide 1 group (blue) and Gold (yellow). Note the fine gold grains associated with sulfides, both within the matrix and within the fractures, as well as coarse and elongated grains filling fracture 1; (b) 1- Three-dimensional image focusing solely on the gold group in sample GSR-CAC-N130, highlighting the grains filling fracture 1; 2- Three-dimensional image focusing solely on the gold group in sample GSR-CAC-N130, emphasizing the grains filling fracture 2 and their spatial relationship with fracture 1; (c) 1- Two-dimensional digital slice image of sample GSR-CAC-N130 showing gold grains

(white) within altered pyrite crystals (lilac); 2- Detail of the three-dimensional reconstruction of sample GSR-CAC-N130 depicting the relationship between Sulfide 1 group (blue) and Gold (yellow).

The Sulfide 1 class in sample GSR-CAC-N130 is quite distinct from its counterpart in sample GSR-P6-L2, appearing highly altered here, with porosity generated by the oxidation of pyrite crystals where, in some cases, gold grains are observed within them (Fig. 18c1,2). The Sulfide 2 class, in this case, appears to be constituted by less altered pyrite grains compared to those assigned to the Sulfide 1 group, showing attenuation similar to the intact pyrite grains comprising the Sulfide 1 group in sample GSR-P6-L2.

As evidenced by the presented data, the coexistence of more than one class of gold in high-grade zones is common. In the case illustrated in Figure 13b, for example, the metal appears to fill fractures and is associated with fuchsite in the matrix present in interstices between pebbles. In Figures 20b and 20c, the presence of at least three distinct groups of gold is notable, which once again appears in the matrix and fills fractures of different directions, and additionally, is associated with pyrite and its alteration products.

Considering that the highest gold grades are located at the top of the metaconglomerates, overlain by quartzite levels that act as permeability barriers (Fig. 14), the intrinsic correlation of high-grade trends with structures, and the presence of gold associated with pyrite and the matrix in spaces between pebbles, it is plausible to suggest the existence of more than one event of enrichment in high-grade zones.

3.5 Discussion

3.5.1 Structural evolution

The current geometry of the Serra de Jacobina and, consequently, the Jacobina Mining District, is the result of a long deformational history that began during the rift phase of the basin (Fig. 19a), where predominantly extensional tectonics generated normal faults, conjugate fracture sets, growth faults, transfer faults, and other extensional features. These, combined with sedimentary structures typical of alluvial fans and intertwined fluvial systems, gave the sediments of the Jacobina Group their initial geometric conformation (Mascarenhas et al., 1992; Pearson et al., 2005; Teles et al., 2015, Teles et al., 2020).

The sedimentary features generated during the basin phase play a fundamental role in controlling gold mineralization in the Jacobina district because it is in the metaconglomerates of the Serra do Córrego Formation that the economically viable

concentration of the metal is found in the region. However, direct relationships between higher-grade zones and specific sedimentary characteristics, such as pebble size, textural or mineralogical maturity, and packing (Gross, 1968), are not observed, making it difficult to directly associate gold mineralization with paleochannels generated in a paleoplacer system.

Subsequently, after the basin phase, the onset of the Paleoproterozoic orogeny, between 1940 and 1910 Ma (Ar/Ar ages, Ledru et al., 1997; Milesi et al., 2002), not only inverted the structures generated in the basin and reshaped the sedimentary layers into tabular bodies trending N-S dipping to the east, but also imposed a new predominantly compressive tectonic regime on the Jacobina Group, with principal stress tensors oriented sub-horizontally in an E-W direction (Fig. 19b). The structures observed during this phase include reverse faults and shear zones F1, foliations S1, mineral stretching lineations Lx1, and N-S axial fold axes, as well as cleavage systems parallel to bedding or possibly to the axial plane of folds generated during this phase.

This phase is of paramount importance to the mineral system in Jacobina, as it is during this phase that the architectural framework of this system is constructed. The basal detachment fault, called the Jacobina fault, as well as its eastern counterparts, the Maravilha fault system and the Pindobaçu fault, associated with a crustal-scale suture zone called the Pindobaçu Suture, constitute essential first-order structures for the circulation of mineralizing fluids that may ascend in the crust until they encounter ideal conditions for deposition.

The progression of compressive deformation and intense shortening of the basin toward the basement, with the verticalization of structures and sedimentary layers, culminates in the generation of lateral escapes and rotation of the σ_1 stress tensors from E-W to NW-SE (dos Santos et al., 2019), initiating a transpressional regime with predominantly sinistral kinematics (phase D2), where high-angle sinistral strike-slip faults of approximately N-S direction and regional dimensions, and E-W-directed antithetic dextral faults are nucleated (Fig. 19c). In transpression, foliations and fracture cleavages sub-parallel to faults F2 and F2b are also generated.

Recent drilling data show that, in the vicinity of the Northern Domain, there is a basement high that may act as a buttress for deformation and promote the nucleation of frontal thrusts verging to the north, generating low-angle reverse faults dipping to the

south, such as the Maricota fault, an important structure located in the southern part of the Northern Domain.

At the end of the orogeny, with the waning of the tectonic forces driving the compressive and transpressional events, the principal stress tensors return, as in the basin phase, to a verticalized position, and the main force acting on the now consolidated Contendas-Jacobina Belt becomes gravity, which acts to reactivate the structures generated in the previous deformational phases, nucleating faults of various orientations that vertically displace the metasedimentary rocks of the Jacobina Group, generating discontinuities.

The timing of the emplacement of mafic and ultramafic bodies present in the Jacobina Mining District is debatable due to the lack of conclusive dating on the age of these rocks. However, in underground mine galleries and drilling, the mafic-ultramafic bodies exhibit N-S penetrating foliations, sub-parallel to regional faults seen in metaconglomerates and quartzites, suggesting that the intrusion of these bodies occurred during a pre-deformational, possibly dike, sill, and lava flow phase, still in the basin phase.

Mapping and understanding the deformational evolution of the system, on scales ranging from regional to microscopic, is of fundamental importance because, in addition to allowing the definition of stress fields and the positioning of paleostressors involved in the generation and maintenance of the pathways through which fluids circulate in each deformational phase, it allows the prediction of how ore-bearing rocks are displaced in events subsequent to mineralization.

According to Cox et al. (2001), rock permeability is a transient property, which can be negatively impacted by processes such as porosity destruction, caused, for example, by rock compaction or closure of intergranular spaces. Thus, the multiple deformational events mapped in this work play a fundamental role in maintaining the permeability of the Jacobina mineral system by repeatedly regenerating this property through the generation of open fracture systems, essential for fluid circulation through the host rocks of mineralization.

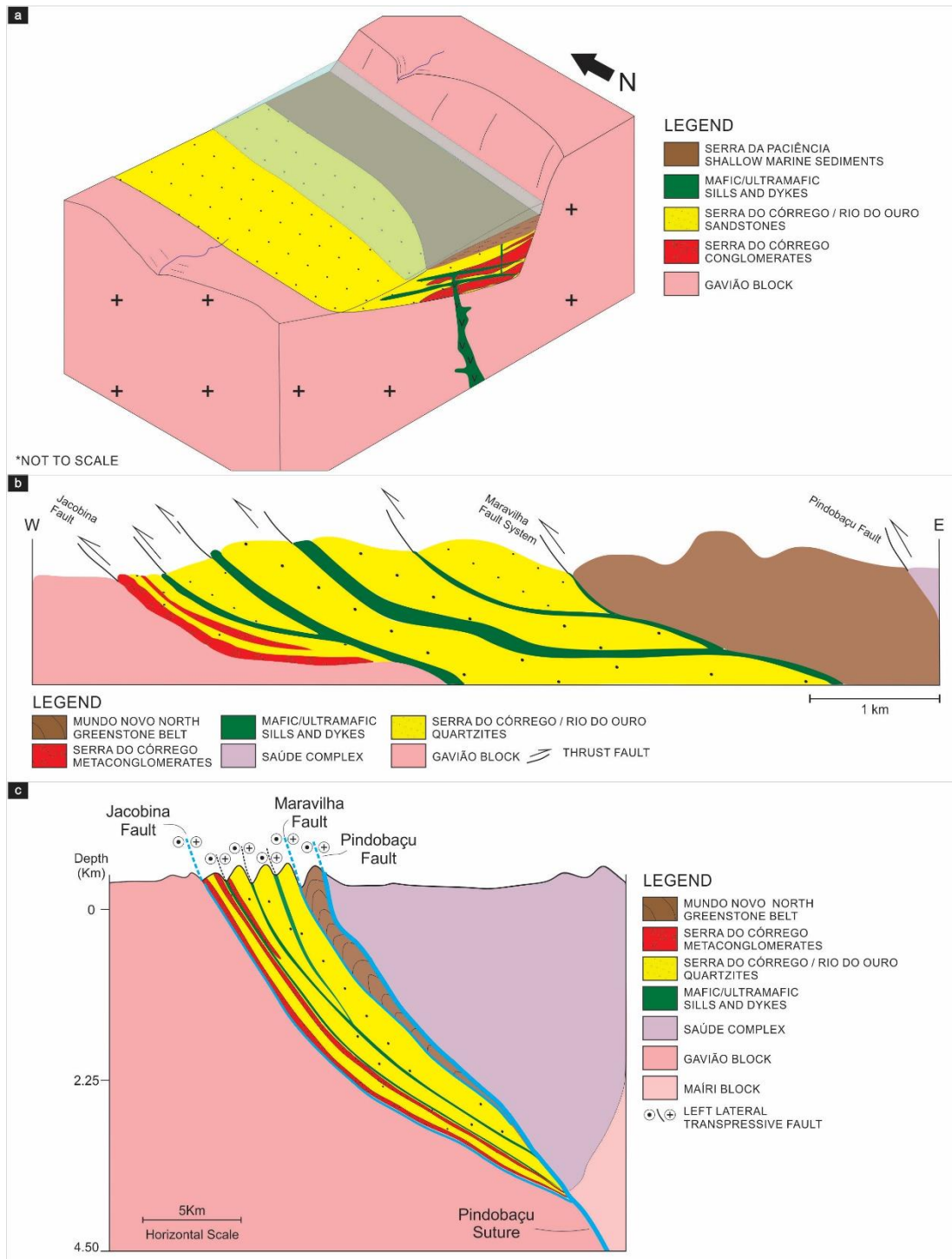


Fig. 19. (a) Schematic drawing of the rift phase during the formation of the Jacobina basin; (b) Schematic section of the compressive phase that led to the inversion of the Jacobina Basin in the Paleoproterozoic and culminated in the formation of the Contendas-Jacobina Lineament (adapted from Teixeira et al., 2001); (c) Schematic drawing of the current configuration of the Jacobina Range and its basement, illustrating the main structures mapped in the study area.

The succession of deformational events experienced by the rocks in the study area, as presented and discussed earlier, has resulted in a complex structural and lithological configuration in the region of the Mining District, as illustrated in the three-dimensional

models constructed from successive surface and subsurface mapping data, combined with diamond drilling data (Fig. 20a,b). This configuration directly influences the establishment and effectiveness of the Jacobina mineral system.

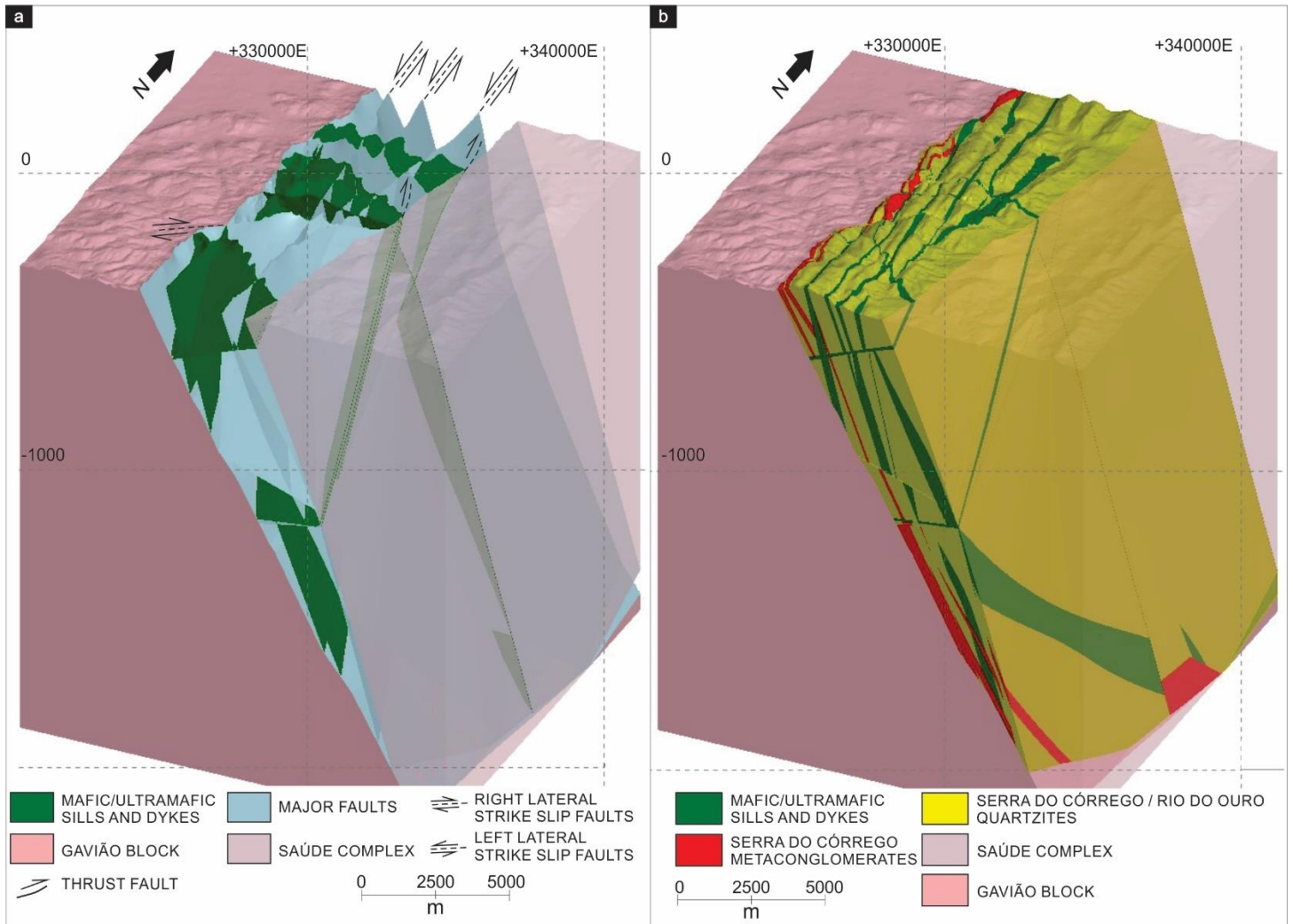


Fig. 20. (a) Three-dimensional structural model of the Jacobina Mining District region, generated from data collected on the surface, underground, and drill holes, illustrating the main structures mapped in the area, their truncation relationships, and kinematics; (b) Three-dimensional geological model of the Jacobina Mining District area, generated from data collected on the surface, underground, and drill holes, illustrating the main lithotypes found in the region and their relationships.

3.5.2 The Jacobina Mineral System

The controversial genesis of gold in the Jacobina Range, with the central debate focusing on the detritic, syngenetic or epigenetic origin of the metal, revolves around three widely accepted models of mineralization. Although differing in the origin of gold itself, there is a common factor in studies conducted for this purpose in the Jacobina District region: the influence of fluid percolation on the current disposition of gold in the Jacobina mineral system.

Bateman (1958), in his work, acknowledges that the geochemical evidence available at the time was insufficient to support an exclusively syngenetic model for Jacobina mineralization, suggesting that some remobilization must have occurred. Gross (1968) adds that the highest gold grades are situated at the top of metaconglomeratic layers, as evidenced by the modeling presented in Figure 16, argues in favor of fluid involvement in the system. Milesi et al. (2002) suggest that first and second-order structures, represented by shear zones, would act as conduits for epithermal fluids, while the metaconglomerates and quartzites of the Serra do Córrego Formation would serve as reservoirs and lithological traps where gold would be precipitated.

In light of current knowledge about the concept of mineral systems, it is possible to propose a holistic model for the control of high-grade ore-shoots in the Jacobina Mining District, which takes into account primarily the architecture and geometry of the mineral system, regardless of the source of gold itself. With the integration of multiscale data presented in this research, ranging from regional to micrometer scales, it is feasible to suggest that there are several indications of epigenetic processes associated with the circulation of mineralizing fluids during the paleoproterozoic orogeny, and consequently the formation of high-grade corridors. In the Jacobina Mining District, we can observe all critical factors of a mineral system strongly conditioned by tectonics: a fertile source associated with a crustal architecture favorable to the percolation of mineralized fluids, which, in the face of transient geotectonic triggers, ascend in the crust to a location of accumulation, preserved in subsequent geological events.

3.5.3 Fertility

Regarding the fertile source responsible for supplying the system with the elements that enrich the mineralizing fluids, it is possible that there is a conjunction of factors in Jacobina leading to the extensive and prolific mineralization observed throughout the region. Considering that the metaconglomerates of the Serra do Córrego Formation exhibit anomalous concentrations of gold virtually throughout their extent, even in small and non-economic values (Gross, 1968), it is plausible to assume that the syngenetic origin of gold plays a fundamental role in regional-scale mineralization. However, in the mines of the Jacobina Mining District, there is no direct relationship observed between high-grade zones and sedimentary features such as paleochannels.

The recent studies conducted by Teles et al. (2020) and Garayp and Frimmel (2023), using Sulfur isotopes and trace elements analyses on Pyrite grains derived from

the Serra do Córrego formation, have presented unequivocal evidence of the association between gold and detrital or syngenetic pyrite, by showing that this group is significantly richer in gold than the epigenetic pyrite also found in the Serra do Córrego metaconglomerates. Additionally, these authors also pointed out that there is an important contribution from hydrothermal activity on the remobilization of elements in the system, as, in both studies, it is stated that epigenetic pyrite might have formed from a fluid-induced recrystallization of the detrital grains. Furthermore, Garayp & Frimmel (2023) concluded that metamorphism and magmatism might have caused the partial dissolution and reprecipitation of minerals, including gold.

Alternatively, authors advocating for hydrothermal models of mineralization (Teixeira et al., 2001; Milesi et al., 2002) propose, with some particularities, that gold would come from hydrothermal fluids generated during the paleoproterozoic orogeny, a context that is quite similar to that found in some of the world's major orogenic gold deposits, where the main source of the large volumes of fluids associated with mineralization controls would be the dehydration of minerals present in rocks rapidly buried during crustal subduction during orogeny building (Gaboury, 2019).

Indeed, the geotectonic environment in which the Jacobina District is situated is quite fertile and has a long history of fluid circulation, from the intrusion of mafic-ultramafic bodies during the basin phase, providing not only fluids but also heat to the system, through the orogeny and the generation of metamorphic fluids deep in the crust, possibly involving previously mineralized metaconglomerates as a source of gold for the enriched fluid.

3.5.4 Geodynamics

The fluid-generating capacity of a system must be associated with tectonic events that promote its ascent in the crust to the host rocks through a favorable architecture for its percolation. At a regional scale, in the case of Jacobina, the evolution of deformation throughout the Paleoproterozoic orogeny is the geodynamic trigger driving the continuous circulation of fluids through the system (Barnicoat et al., 1997 unpublished; Teixeira et al., 2001; Milesi et al., 2002).

The multiple tectonic pulses involved in the inversion of the basin during the convergent phase of the orogeny would then be responsible for promoting the movement of fluids generated at depth through crustal-scale structures (Teixeira et al., 2001; Milesi

et al., 2002; Pearson et al., 2005), mineralizing distinct host rocks, including the metaconglomerates of the Serra do Córrego Formation. As evidenced in this study, at least three families of structures generated throughout the orogen's evolution are mineralized, indicating the circulation of gold-enriched fluids at different times in Jacobina's deformational history.

3.5.5 Architecture

The parameter of architecture is of paramount importance for understanding the mineral system as it is the main controller of the paths through which mineralizing fluids circulate and interact with host rocks, taking into account the influence of the system's geometry on the generation of regions conducive to fluid accumulation in structural traps zones, as well as considering the characteristics of the rocks present in the deposit and their contribution to the roles of potential host rocks and lithological or chemical traps.

The architecture of the Jacobina mineral system is easily correlated with that of several world-class deposits associated with orogenic environments, in the sense that the primary control of mineralization is associated with first-order structures that act as conduits for the ascent of fluids enriched by the crust during tectonic events (Groves et al., 2020). In the Jacobina Mining District, the Jacobina, Maravilha, and Pindobaçu faults are the main representatives of this class of structures, which, associated with the Pindobaçu suture (Fig. 19c), could act as regional-scale channels for fluid percolation.

In the mines of the district, primary control is highly relevant because the tabular geometry of the metaconglomerate bodies, oriented N-S, is concordant with the N-S first-order structures, producing a conducive scenario for the interaction of fluids circulating through these structures with the metaconglomerates they percolate. Both regionally and at the deposit scale, this condition may be responsible for the mineralization, even at marginal grades, of practically the entire extent of the metaconglomerates of the Serra do Córrego Formation.

More specifically, at the Morro do Vento mine, belonging to the Central Domain, the association of grades with first-order structures is highly relevant, as in the southern portion of the mine, the prolific Main Reef is strongly associated with N-S shear zones, and in the northern portion, the Basal Reef, where the highest grades of the Central Domain are found, is in direct contact with the Jacobina fault (Fig. 5, Fig. 19b, c).

While first-order structures control the bulk of the mineralization at the regional scale, the formation of high-grade corridors depends on their interaction with second-order structures that act to concentrate and channel the flow of fluids (Groves et al., 2020). These structures, which may originate from pre-orogenic weak zones, such as sin-rift faults, or lithological contacts, are better represented in the Jacobina Mining District by faults approximately oriented E-W.

Observing, with the use of grade interpolations of channel samples (Fig. 13a), the behavior of grades in underground mine galleries, it is noted that the highest gold grades are concentrated in zones of intersection of N-S first-order structures with E-W second-order structures, forming continuous corridors both laterally and vertically.

Among the structural domains comprising the Jacobina Mining District, the importance of intersections of first and second-order structures in controlling mineralized zones is more evident in the Southern and Central domains, where the tabular geometry of the metasedimentary bodies plays a subordinate role in fluid accumulation. On the other hand, in the Northern Domain, in addition to structure intersections, the folded geometry of the bodies, generating anticlines and synclines, appears to strongly influence the migration and concentration of fluids in regions closer to the hinges.

In this domain, as in the others, the metaconglomerates act as permeable zones due to their primary or secondary porosity and permeability (Gross, 1968; Teixeira et al., 2001; Milesi et al., 2002; Pearson et al., 2005), imposed by deformation and the generation of interconnected fracture systems, while the quartzites act as seals, given their greater resistance to fluid percolation compared to the metaconglomerates. However, as illustrated in Figure 8, the Northern Domain has more horizontal layers than the others, mainly in the central portion of the Canavieiras Sul mine and the northernmost portion of the Canavieiras Norte mine, causing the richest metaconglomerate reefs in these mines (LVLPC, MU, and LU) to be confined between two large quartzite packages, creating a limited corridor for fluid circulation in the metaconglomerates between these two efficient seals. Additionally, the MU and LU Reefs, bearing the highest grades in the entire district, are characterized by the intercalation, whether sedimentary or tectonic, of thin lenses of metaconglomerates and quartzites, reinforcing the importance of host/trap relationships.

Furthermore, the Northern Domain presents a unique geometry within the Jacobina Mining District, with the formation of structural traps in the form of large open

anticlines, where most of the highest-grade samples in the entire district are concentrated (Fig. 13c). The existence of first and second-order structures, which act as conduits and channelers of mineralized fluid flow, common to all three domains, combined with the unique geometry of the metaconglomerates in the Northern Domain, creates the ideal scenario for the concentration of fluids from more than one tectonic pulse during events related to system enrichment, providing the Northern Domain with favorable conditions for the formation of higher-grade zones than in adjacent domains.

Indeed, the analysis of microtomography results from sample GSR-CAC-N130 allows us to conclude that at least three distinct types of gold coexist in it, with the metal being free in the matrix, within oxidized pyrites, and filling two planes of sub-orthogonal fractures, which points to repeated fluid entry into the system at the same location, a fact facilitated by the folded geometry of the Canavieiras Sul, Central, and Norte mines.

3.5.6 Preservation

The final critical factor for a mineral system is its preservation throughout the subsequent geological history following mineralization. In the case of the Jacobina Mining District, there are no records of relevant deformational events after the Paleoproterozoic orogeny, resulting in the preservation of the original architecture of the system and the gold deposition sites. Additionally, the fact that the metaconglomerates acting as reservoirs in the Jacobina deposit are composed of 96 to 99% quartz, and the lithological traps are predominantly extremely pure quartzites, makes these rocks highly resistant to physical and chemical weathering, contributing to the preservation of their integrity even after approximately 2 billion years.

3.5.7 The Jacobina Mineral System Dynamics

The conjunction of critical factors in a mineral system is determinant for its effectiveness and, consequently, for the concentration of ore in significant quantities. In the Jacobina Mining District, the fertile environment and geological history from Archean sedimentation to the end of the Paleoproterozoic orogeny constitute the ideal scenario for the formation of a large-scale deposit, with a mineral inventory of approximately 10 million ounces of gold.

Understanding the dynamics established in Jacobina begins with the controversial source of the metal, which, for some authors (Bateman, 1958; Cox, 1967; Gross, 1968; Teles et al., 2020, Garayp and Frimmel, 2023), stems from the deposition of gold

associated with detrital or diagenetic pyrite in the metaconglomerates of the Serra do Córrego Formation in an Archean basin, while for others (White, 1956; Davidson, 1957; Ledru et al., 1997; Milesi et al., 2002; Teixeira et al., 2001, 2010, 2019), the metal originates from metamorphic fluids generated in the Paleoproterozoic orogeny.

The fact is that, for mining purposes, understanding the current geometry and generating prospective models of high-grade zones in the Mining District, outweighs the relevance of determining the origin of gold itself, since there is consensus in the literature about the importance of fluid circulation through the system, whether remobilizing the gold associated to syngenetic pyrite or transporting epigenetic gold, which has proven, by the evidence shown in this work, to be of significant importance to the generation of high-grade shoots.

Therefore, the Paleoproterozoic orogeny acted as the driving mechanism for the movement of metamorphic fluids through the Jacobina mineral system, with transient tectonic events during the collision of the Paleoarchean block being responsible for providing the necessary energy for the ascent of metamorphic fluids generated at depth through structures acting as conduits, circulating and interacting with host rocks until the ideal conditions for gold deposition are reached. Miranda et al. (2021) has also pointed to a magmatic influence over gold remobilization using fluid inclusion data on gold bearing quartz veins.

The main conduits for the ascent of metamorphic fluids through the crust and for their percolation into the rocks constituting the Serra do Córrego Formation would be the large N-S first-order structures, such as the Pindobaçu suture and the Jacobina, Maravilha, and Pindobaçu faults (Fig. 19c). The fluids are then channeled and concentrated in zones of intersection between the N-S first-order structures and second-order E-W structures, promoting the concentration of high gold grades in these zones.

In turn, the metaconglomerates in the Mining District present the best conditions for hosting mineralization, as their primary porosity and permeability, associated with secondary permeability generated during deformation, facilitated the circulation of enriched fluids, which have concentrated when they have encountered lithological traps, such as quartzites and mafic-ultramafic bodies, or structural traps, such as antiforms. It is important to emphasize here that secondary porosity is highly relevant for fluid circulation at the deposit and regional scale, since the gold found in quartzites and ultramafic rocks is restricted to fracture and fault planes.

3.6 Conclusions

The Jacobina Mineral System exhibits unique features distinguishing it from other paleoplacer gold deposits globally. Its complex structural framework, shaped by a prolonged and complex deformational history from an Archean rift basin with extensional tectonics to a Paleoproterozoic orogeny with dominant compressive tectonics, is essential for the formation of a world-class gold deposit. Key conclusions from the study include:

1. **Structural and Geological Framework:** The intricate structural framework and deformational history have been crucial in forming its fertile, geodynamic, and architectural characteristics necessary for high-grade gold deposits.
2. **Deformational Phases and Mineralization:** Critical parameters at the deposit scale reveal impact of regional deformational phases on the geometric and architectural shape of mineralized bodies, aiding in the identification of high-grade zones and optimizing exploration and mining activities.
3. **Role of Structures:** High-grade gold corridors are intrinsically linked to structures. First-order, high-angle, N-S oriented structures acted as conduits for mineralized fluids, while second-order, E-W oriented structures served as permeability barriers, promoting fluid accumulation at intersections, creating high Au concentration regions.
4. **Domain-Specific Insights:** In the North Domain, antiformal structures are significant fluid accumulation zones, generating the highest gold grades among the studied structural domains.
5. **Fluid Circulation:** Tectonic events created and maintained favored permeability zones, allowing continuous fluid presence in the system, which played a crucial role in gold remobilization and concentration.
6. **Differentiation of High-Grade Zones:** Distinguishing high-grade zones into distinct structural domains is essential, as the controls on these zones differ, particularly in the directions and dips of key structures, using oriented samples, drillhole data, and structural databases to determine directions of gold-bearing structures.
7. **Advanced Techniques for Exploration:** Techniques like X-ray computed microtomography and 3D lithostructural modeling are valuable for visualizing high-grade zones and understanding the factors differentiating them, aiding in more precise exploration.

8. **Prospective Model Development:** The analysis of critical factors in the Jacobina region has led to a comprehensive understanding of fluid pathways, gold remobilization, and metal concentration sites, resulting in a robust prospective model for high-grade zones applicable at deposit and regional scales.

3.7 Acknowledgements

We would like to thank Juliano José de Souza and the exploration geology team of Jacobina Mineração e Comércio for their support, both moral, financial, and providing the necessary data for this research, as well as the Laboratory of Rock Physical Properties at the University of Brasília for their support in conducting the Micro-CT studies. This work was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Financing Code 001.

3.8 References

- Allmendinger, R. W., Cardozo, N., and Fisher, D., 2012, *Structural Geology Algorithms: Vectors and Tensors*: Cambridge University Press, Cambridge, 302 p.
- Andrew, B.S. Recognising cryptic alteration surrounding the Mount Isa Copper Deposits: implications for controls on fluid flow, and mineral exploration: PhD thesis, Waikato, New Zealand, The University of Waikato, 248 p.
- Barbosa, J.S.F., Sabaté, P., Moacyr, M.M., 2003. O Cráton do São Francisco aa Bahia: uma síntese. *Revista Brasileira de Geociências* 33 (1), 3–6.
- Barbosa, J.S.F., Sabaté, P., 2004. Archean and paleoproterozoic crust of the São Francisco craton, Bahia, Brazil: geodynamic features. *Precambrian Res.* 133, 1–27.
- Bateman, J.D. (1958) Uranium-bearing auriferous *Reef* at Jacobina, Brazil. *Econ. Geol.* 53:417–425
- Cnudde, V., Boone, M.N, 2013. High resolution X-Ray computed tomography in geosciences: a review of the current technology and applications. *Earth Sci. Rev.*123, 1-17.
- Da Costa, M. F., Kyle, J.R., Lobato, L. M., Ketcham, R.A., Silva, R.C.F., Fernandes, R.C.,2022. Orogenic Gold in three-dimensions: A case study of distinct mineralization styles at the world-class Cuiabá deposit, Brazil, using high-resolution X-ray, computed tomography on gold particles. *Ore Geol. Rev.* 140.
- Cowan, E.J. 2022. Deposit-scale Structural analysis from drill hole assay data using locally varying anisotropies (LVA)—a catalyst for structural geological enlightenment? *AIG Bulletin*, 72, 12–19.
- Cowan, E.J. 2020. Deposit-scale structural architecture of the Sigma-Lamaque gold deposit, Canada—insights from a newly proposed 3D method for assessing structural controls from drill hole data. *Mineralium Deposita* 55, 217–240.

- Cowan, E.J. 2014. 'X-ray *Plunge* Projection'— Understanding Structural Geology from Grade Data, in Mineral Resource and Ore Reserve Estimation — The AusIMM Guide to Good Practice, second edition, p. 207–220.
- Cowan, E.J., Beatson, R.K., Fright, W.R., McLennan, T.J., and Mitchell, T.J. 2002. Rapid Geological Modelling. Applied Structural Geology for Mineral Exploration and Mining, International Symposium Abstract Volume (ed: S. Vearncombe). AIG Bulletin, 36, 39–41.
- Cox, D.P. 1967. Regional environment of the Jacobina auriferous conglomerate, Brazil. *Econ Geol* 62:773–780.
- Cox, S.F., Knackstedt, M.A., Braun, J., 2001. Principles of structural control on permeability and fluid flow in hydrothermal systems. *Econ. Geol. Rev.* 14, 1–24.
- Dos Santos F.P., Chemale Junior F., Meneses A.R.A.S. (2019) The nature of the Paleoproterozoic orogen in the Jacobina Range and adjacent areas, northern São Francisco Craton, Brazil, based on structural geology and gravimetric modelling. *Precambr. Res* 332:1–2.
- Ferreira da Silva, G., Silva, A. M., Toledo, C. L. B., Chemale Junior, F., & Klein, E. L. (2022). Predicting mineralization and targeting exploration criteria based on machine-learning in the Serra de Jacobina quartz-pebble-metaconglomerate Au-(U) deposits, São Francisco Craton, Brazil. *Journal of South American Earth Sciences*, 116, 103815. <https://doi.org/10.1016/j.jsames.2022.103815>
- Frimmel H.E., Nwaila G.T., 2020. Geologic evidence of syngenetic gold in the Witwatersrand goldfields, South Africa. In: Sillitoe, R.H., Goldfarb, R.J., Robert, F., Simmons, S.F. (eds) *Geology of the World's Major Gold Deposits and Provinces*. Soc Econ Geol Spec Publ 23: 645–668.
- Gaboury, D., 2019. Parameters for the formation of orogenic gold deposits Parameters for the formation of orogenic gold deposits. *Appl. Earth Sci.* 2019, 128, 124–133.
- Garayp, E., Frimmel, H.E. A modified paleoplacer model for the metaconglomerate-hosted gold deposits at Jacobina, Brazil. *Miner Deposita* (2023).
- Gross, W.H., 1968. Evidence for a Modified Placer Origin for Auriferous Conglomerates, Canavieiras Mine, Jacobina, Brazil, vol. 63. *Economic Geology*, Lancaster, pp. 271-276.
- Groves, D.I., Santosh, R.J., Zhang, L., 2020. A scale-integrated exploration model for orogenic gold deposits based on a mineral system approach. *Geosci. Front.* 11, 719–738.
- Hronsky, J., Groves, D., 2008. Science of targeting: Definition, strategies, targeting and performance measurement. *Australian Journal of Earth Sciences* 55, 3–12.
- Knox-Robinson, C.M., Wyborn, L.A.I., 1997. Towards a holistic exploration strategy: using geographic information systems as a tool to enhance exploration. *Aust. J. Earth Sci.* 44, 453–463.
- Kyle, J.R., Ketcham, R.A., 2015. Application of high-resolution X-ray computed tomography to mineral deposit origin, evaluation, and processing. *Ore Geol. Rev.* 65, 821-839.

- Ledru, P., Johan, V., Milési, J.P., Tegye, M., 1994. Markers of the last stages of the Palaeoproterozoic collision: evidence for a 2 Ga continent involving circum-South Atlantic provinces. *Precamb. Res.*, Amsterdam 69 (1-4), 169–191.
- Ledru, P., Milési, J.P., Sabaté, P., Malulki, H., 1997. Foreland basins and gold-bearing conglomerates: a new model for Jacobina Basin (São Francisco province, Brazil). *Precamb. Res.*, Amsterdam 86, 155–176.
- Leite, C.M.M., 2002.
- Leo, G.N., Cox, D.P., Carvalho, J.P.P., 1964. Geologia da parte sul da Serra de Jacobina, Bahia, Brasil. DNPM, Rio de Janeiro.
- Marrett, R. A., and Allmendinger, R. W., 1990, Kinematic analysis of fault-slip data: *Journal of Structural Geology*, v. 12, p. 973-986.
- Martin, H., Peucat, J.J., Sabate, P., Cunha, J., 1997. Crustal evolution of the early archaean of south America: example of the sete voltas massif, Bahia state, Brazil. *Precambrian Res.* 82, 35–62.
- Leo, G.N., Cox, D.P., Carvalho, J.P.P., 1964. Geologia da parte sul da Serra de Jacobina, Bahia, Brasil. DNPM, Rio de Janeiro.
- Mascarenhas, J.F., Ledru, P., Souza, S.L., Conceição Filho, V.M., Melo, L.F.A., Lorenzo, C.L., Milési, J.P., 1998. Geologia e recursos minerais do Grupo Jacobina e da parte sul do Greenstone Belt de Mundo Novo. *Série de Arquivos Abertos* 13, Companhia Baiana de Recursos Minerais, Salvador pp 55.
- McCuaig, T.C., Hronsky, J.M.A., 2014. The Mineral System Concept: the Key to Exploration Targeting. *SEG 2014: Building Exploration Capability for the 21st Century*, pp. 153–175.
- K. R. McClay 1987. *The Mapping of Geological Structures*. Geological Society of London Handbook, vi + 161 pp. Milton Keynes: Open University Press; New York, Toronto: Halsted Press, John Wiley. Price £7.95 (paperback). ISBN 0 335 15096 9(OUP); 0 470 20355 2 (Halstead).
- Milési, J.P., Ledru, P., Johan, V., Marcoux, E., Mougeot, R., Lerouge, C., Respaut, J.P., Sabaté, P., 1996. Hydrothermal and metamorphic events related to the gold mineralizations hosted within detrital sediments in the Jacobina basin Bahia, Brazil *Anais do XXXIX Congresso Brasileiro de Geologia*, Salvador, vol. 7, pp. 218 – 220.
- Milési, J.P., Ledru, P., Marcoux, E., Mougeot, R., Johan, V., Lerouge, C., Sabaté, P., Bailly, L., Respaut, J.P., Skipwith, P., 2002. The Jacobina Paleoproterozoic gold-bearing conglomerates, Bahia, Brazil: a “hydrothermal shear-reservoir” model. *Ore Geol Rev* 19:95–136.
- Miranda, D. A., Misi, A., Klein, E.L., Castro, M.P., Queiroga, G., 2021. A mineral system approach on the Paleoproterozoic Au-bearing quartz veins of the Jacobina Range, northeastern of the São Francisco Craton, Brazil. *J. South Am. Earth. Sci.* 103080.
- Molinari, L., Scarpelli, L., 1988. Depósitos de Ouro de Jacobina. *Principais Depósitos Minerais Do Brasil* DNPM Brazil 3:463–47.
- Nutman A. P. and Cordani U. G. (1993) SHRIMP U-Pb zircon geochronology of Archean granitoids from the Contendas-Mirante area of the São Francisco Craton, Bahia, Brazil. *Precam. Res.* 163, 179–188.

- Pearson, W.N., Macedo, P. M., Rubio, A., Lorenzo, C. L., Karpeta, P., 2005. Geology and gold mineralization of the Jacobina Mine and Bahia Gold Belt, Bahia, Brazil, and a comparison to Tarkwa and Witwatersrand. Window to the World: 2005 Symposium Proceedings Geological Society of Nevada, Reno/Sparks Nevada, pp 757–785.
- Peucat J. J., Mascarenhas J. F., Barbosa J. S. F., Souza S. L., Marinho M. M., Fanning C. M. and Leite C. M. M. (2002) 3.3Ga SHRIMP U-Pb zircon age of a felsic metavolcanic rock from the Mundo Novo greenstone belt in the São Francisco Craton, Bahia (NE Brazil). J. South Amer. Earth Sci. 15, 363–373.
- Reis, C, *et al.*, 2021. Projeto Integração Geológica e Avaliação do Potencial Metalogenético da Serra de Jacobina e do Greenstone Belt de Mundo Novo. Informe de Recursos Minerais, Série Províncias Minerais do Brasil 31 CPRM pp 169.
- Sabaté, P., Marinho, M.M., Vidal, P., Caen-Vachette, M., 1990. The 2-Ga peraluminous magmatism of the Jacobina-Contendas Mirante belts (Bahia, Brazil): geologic and isotopic constraints on the sources. Chem. Geol. 83:325–338.
- Santo-Pinto, M., Peucat, J.J., Martin, H., Barbosa, J.S.F., Fanning, M., Cocherie, A., Paquette, J.L., 2012. Crustal evolution between 2.0 and 3.5 Ga in the southern Gavião block (Umburanas-Brumado-Aracatu region), São Francisco Craton, Brazil: a 3.5-3.8 Ga proto-crust in the Gavião block? Journal of South American Earth Sciences 40, 129–142.
- Santos, F. P. dos, Chemale Jr., F., Meneses, A. R. A. S., 2019. The nature of the Paleoproterozoic orogen in the Jacobina Range and adjacent areas, northern São Francisco Craton, Brazil, based on structural geology and gravimetric modeling. Precambrian Research, 105391
- Soares, E.S., Lopes, R.G., Marsden, H., Vasquez, L., Iturralde, C., Bernier, S., 2020. NI 43–101 Technical Report Jacobina Gold Mine, Bahia State, Brazil. System for Electronic Document Analysis and Retrieval (SEDAR) Canadian Securities Administrator 190 pp. http://s28.q4cdn.com/334653565/files/doc_downloads/YamanaJacobina-NI-43-101-May-29-2020.pdf
- Teixeira, J.B.G., de Souza, J.A.B., da Silva, M.G., Leite, C.M.M., Barbosa, J.S.F., Coelho, C.E.S., Abram, M.B., Conceição Filho, V.M., Iyer, S.S.S., 2001. Gold mineralization in the Serra de Jacobina region, Bahia, Brazil: tectonic framework and metallogenesis. Miner. Deposita 36:332–344.
- Teixeira, J.B.G., da Silva, M.G., Misi, A., Cruz, S.C.P., Sá, J.H.S., 2010. Geotectonic setting and metallogeny of the northern São Francisco craton, Bahia, Brazil. J South Am Earth Sci 30:71–83.
- Teixeira, J.B.G., Misi, A., da Silva, M.G., Brito, R.S.C., 2019. Reconstruction of the Precambrian terranes of Northeastern Brazil along Cambrian *strike-slip* faults: a new model of geodynamic evolution and gold metallogeny in the State of Bahia. Braz J Geol 49(3):1–20.
- Teles, G., Chemale, F. Jr., Oliveira, C.G., 2015. Paleoproterozoic record of the detrital pyrite-bearing, Jacobina Au-U deposits, Bahia, Brazil. Precamb. Res. 256:289–313.
- Teles, G.S., Chemale, F. Jr., Avila, J.N., Ireland, T.R., Dias, A.N.C., Cruz, D.C.F., Constantino, C.J.L., 2020. Textural and geochemical investigation of pyrite in Jacobina Basin, São Francisco Craton,

Brazil: Implications for paleoenvironmental conditions and formation of pre-GOE metaconglomerate-hosted Au-(U) deposits. *Geochim Cosmochim Acta* 273:331–353.

White, M.G., 1961. Origin of uranium and gold in the quartzite-conglomerate of the Serra de Jacobina. USGS, Washington (Professional Paper, 424-B).

Wyborn, L.A.I., Heinrich, C.A., Jaques, A.L., 1994. Australian proterozoic mineral systems: essential ingredients and mappable criteria. In: AUSTRALIAN INSTITUTE of MINING and METALLURGY ANNUAL CONFERENCE, 1994, Melbourne. Proceedings [...] Melbourne. Australian Institute of Mining and Metallurgy, pp. 109–115.

Zincone S. A., Oliveira E. P., Laurent O., Zhang H. and Zhai M.(2016) 3.30 Ga high-silica intraplate volcanic-plutonic system of the Gavião Block, São Francisco Craton, Brazil: evidence of anintracontinental rift following the creation of insulating continentalcrust. *Lithos* 266–267, 414–434.

Capítulo 4 – Considerações finais

O Distrito Mineiro de Jacobina exibe particularidades singulares em comparação com outros depósitos de ouro em paleoplacer em todo o mundo. Sua intrincada estrutura é o resultado de uma longa história de deformações, que se iniciou em uma bacia Arqueana e culminou na *orogenia* paleoproterozoica, fornecendo ao sistema mineral os elementos necessários de fertilidade, geodinâmica e arquitetura para a formação de um depósito aurífero de classe mundial.

A análise em nível de depósito dos parâmetros críticos presentes em Jacobina, revelou-se efetiva na identificação das fases regionais de deformação e seu impacto na geometria e arquitetura dos corpos mineralizados no Distrito Mineiro. Essa etapa foi crucial para compreender os fatores envolvidos na formação de zonas de alta mineralização, permitindo otimizar a prospecção e guiar as atividades de exploração e mineração nas minas do Distrito.

Observou-se que, embora a mineralização economicamente viável esteja restrita aos metaconglomerados da Formação Serra do Córrego, o relacionamento intrínseco dos corredores de alto teor de ouro com as estruturas é inegável. Estruturas de primeira ordem, predominantemente orientadas no sentido N-S, atuam como condutos para fluidos mineralizados durante eventos tectônicos transientes, facilitando a circulação desses fluidos através das rochas encaixantes da mineralização em todo o depósito. Estruturas de segunda ordem, geralmente orientadas no sentido E-W, funcionam como barreiras de permeabilidade ou zonas de baixa pressão, resultando na acumulação de fluidos mineralizados nas interseções destas com as estruturas de primeira ordem, criando assim

regiões de alta concentração de ouro, em todos os domínios estruturais estudados. No Domínio Norte, estruturas antiformais desempenham um papel crucial na acumulação de fluidos, gerando concentrações significativamente mais elevadas de ouro do que nos demais domínios estruturais estudados.

Os eventos tectônicos desempenharam um papel crucial na geração e manutenção de zonas de permeabilidade favoráveis para a circulação de fluidos no sistema mineral. Desta forma, a presença contínua de fluidos no sistema, desde a entrada de diques e sills máficos e ultramáficos até a intrusão de granitoides, foi fundamental para a remobilização do ouro e reconcentração do metal em zonas de alto teor.

Existem variações nos controles das zonas de alto teor entre as minas estudadas, indicando a importância da individualização das minas de Jacobina em diferentes domínios estruturais para atividades de exploração e mineração, aqui subdivididas da seguinte forma: (i) Domínio Norte, constituído pelas minas Canavieiras Sul, Canavieiras Central e Canavieiras Norte; (ii) Domínio Central, constituído pelas minas Morro do Vento e Morro do Cuscuz; (iii) Domínio Sul, constituído pela mina João Belo Norte.

A avaliação dos parâmetros críticos do sistema mineral em Jacobina e sua influência nos controles da mineralização, em nível de depósito, elucidou questões importantes sobre a geometria e localização das zonas de maior concentração da mineralização. Isso servirá como um guia eficaz para estudos futuros mais detalhados, utilizando técnicas como microtomografia computadorizada de raios-X e modelagem litoestrutural tridimensional para visualizar as zonas de maior mineralização e determinar as direções das estruturas portadoras de ouro.

Em suma, a análise conjunta dos fatores críticos do sistema mineral em Jacobina foi essencial para compreender os caminhos pelos quais os fluidos remobilizaram e precipitaram o ouro, permitindo a geração de um modelo prospectivo robusto e preciso para as zonas de alto teor, aplicável em escala de mina, de depósito e, possivelmente, em escala regional. Trabalhos futuros envolvendo mapeamentos sistemáticos contínuos em subsolo podem ser essenciais para a coleta de amostras orientadas, ideias para o aprofundamento do estudo da circulação de fluidos mineralizados, incluindo seus caminhos e zonas de deposição. Estudos geoquímicos e isotópicos com rastreamento de traçadores de alterações associadas ao ouro podem, também, ser úteis para a geração de modelos prospectivos regionais, a exemplo do trabalho realizado por Andrew (2020), no depósito de Mount Isa, Austrália. Trabalhos utilizando geofísica podem ser extremamente

úteis para delimitar estruturas importantes e colaborar na interpretação do movimento de grandes estruturas, facilitando a prospecção de alvos ainda inexplorados.