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PÓS-GRADUAÇÃO EM GEOCIÊNCIAS
ÁREA METALOGÊNESE

Jane Nobre-Lopes

DIAGENESIS OF THE DOLOMITES HOSTING Zn/Ag MINERAL DEPOSITS IN THE BAMBUÍ GROUP AT JANUÁRIA REGION-MG.

Tese apresentada ao Instituto de Geociências como parte dos requisitos para obtenção do título de Doutor em Ciências.

Orientador: Prof. Dr. Job Jesus Batista
Co-orientador: Prof. Dr. Eric W. Mountjoy

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To Anita and Eric Mountjoy

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RESUMO

A pesquisa efetuada na região de Januária teve por objetivo definir as relações existentes entre as mineralizações de Zn/Ag que ocorrem encaixados em dolomitos brechados da Formação Sete Lagoas (Grupo Bambuí), na região de Januária, MG.

A definição de como e quando se formaram os dolomitos é fundamental para se entender a evolução das rochas carbonáticas, as relações existentes entre a sedimentação carbonática, os processos diagenéticos e sua relação com os depósitos minerais. A identificação de discontinuidades da bacia e suas relações com as mineralizações também foram investigadas.

A Formação Sete Lagoas foi informalmente dividida em 7 membros agrupados em 3 principais ciclos de sedimentação, denominados basal, intermediário e superior. O ciclo basal é constituido pelos membros calcilutitos argilosos (basal) e calciruditos (1 e 2), interpretados como representando um intervalo regressivo, com os sedimentos depositados numa plataforma carbonática de baixa energia, cortada por canais de maré e esporadicamente afetada por tempestades. A sucessão intermediária é composta pelos membros calcarenito dolomítico (3), dolomito (4), stromatolito dolomítico (5) e dolomito oolítico, intraclástico (6) e da unidade inferior (7A) do membro 7, dololutito.
A interpretação geral desse ciclo é que ele representaria uma sucessão regressiva após uma transgressão ocorrida quando da deposição do membro 3, em *offshore*, passando por depósitos de *shoreface* com barreira recifal, estromatolítica, ambiente lagunar, praias e planícies de marés. O ciclo intermediário termina com exposição subaérea da plataforma carbonática. Não foram encontradas evidências que confirmassem a possível discontinuidade, resultante de exposição subaérea, que teria atuado sobre sedimentos do membro 6. A sucessão superior é composta por pequenos ciclos regressivos de planícies de marés representando uma sucessão progradante em ambientes de baixa energia. As três sucessões são consideradas como compondo um conjunto regressivo de parassequencias. Sedimentos pelíticos da Formação Serra de Santa Helena encerraram a sedimentação carbonática da Formação Sete Lagoas.

Com relação a modificações diagenéticas, os carbonatos apresentam feições de alterações diagenéticas em ambientes subaéreos (tepees, gretas de ressecação, cimentação vadosa e pequenas cavidades relacionadas a dissolução meteórica), submarino, incluindo aí ambientes de intermaré (cimento isópaco acicular ao redor de aloquímicos interpretado como representando cimentação tipo *beachrock*) e em subsuperfície. Feições diagenéticas de subsuperfície são predominantes e incluem, entre outras, compactação, cimentação por calcita espática, dissolução hidrotermal, dolomitização, sulfetos e silicato de Zn, calcita espática de cristalinidade grossa (LCC), fluorita e betumem.

Os dolomitos que hospedam os depósitos minerais são compostos por dolomitos de substituição (precoce e tardia) e cimentos dolomíticos, os quais foram intensamente afetados por dissolução/collapso, gerando brechas. Vários tipos de dolomitos foram identificados, mas apenas os mais importantes serão aqui abordados. Em ondem paragenética, os mais importantes são os dolomitos microcristalinos de substituição precoce (McCD), os dolomitos de cristalinidade média (MCD) e os de cristalinidade grossa (CCD), que são de substituição tardia. Dolomita de cristalinidade muito grossa (VcCD), saddle dolomita (SD) e dolomita de cristalinidade muito fina (VfCD) são cimentos dolomíticos.

McCD afeta sedimentos do membro 7 e 5; MCD e CCD são abundantes e afetam litologias dos membros 4 e 6. VcCD e SD ocorrem intimamente associadas e embora predominem no membro 6, são comuns no membro 7, cortando a

suposta superfície de exposição subaérea que teria ocorrido sobre o membro 6. SD ocorre na forma romboédrica, mais comum e precoce em relação à forma simétrica, que é de cor branca leitosa. VfCD é restrita a zonas de brechas de dissolução/ colapso e é tardia em relação às outras dolomitas, exceto possivelmente a SD branca.

Os diversos tipos de dolomitos e os calcários basais foram analisados para isótopos estáveis e também para Sr. Os resultados das análises de C/O tem como referencia o PDB.

Amostras selecionadas de calcários que apresentam o mínimo de alteração diagenética, e não contem argilo-minerais foram analisadas para C/O e $^{87}Sr/^{86}Sr$ e os resultados obtidos a partir dessas amostas são considerados como representando a provável composição isotópica da água do mar quando da deposição dos sedimentos da Formação Sete Lagoas; esses resultados serão utilizados como referência para avaliar as variações isotópicas nas outras fases diagenéticas analisadas.

Os resultados isotópicos de Sr permitem ainda avaliar a idade de deposição da Formação Sete Lagoas, estimada como tendo ocorrido em torno de 590 a 600Ma.

As amostras analisadas são microamostras e representam as fases diagenéticas já mencionadas.

Valores de $\delta^{18}O$ (PDB) situados entre -6.11 to -6.56‰ (média = -6.39) e valores de $\delta^{13}C$ variando entre 0.26 to 0.58‰ (média = 0,42‰),.são considerados como representativos da água do mar à época da deposição da Formação Sete Lagoas. A relação $^{87}Sr/^{86}Sr$ da água do mar nesse mesmo oceano é situada entre 0.7076 and 0.7079, com base em calcários que ocorrem na base da seção.

McCD: valores de $\delta^{18}O$ permitem considera-los como tendo se formado a partir da água do mar na época da deposição da Formação Sete Lagoas, ou ligeiramente modificada. A relação $^{87}Sr/^{86}Sr$ obtida é ligeiramente superior à definida para a água do oceano Neoproterozóico da Formação Sete Lagoas, o que sugere modificações da composição original, por fluidos diageneticamente tardios.

MCD/CCD: os valores de $\delta^{18}O$ são ligeiramente depletados em relação à presumível composição isotópica da água do mar e os valores de $^{87}Sr/^{86}Sr$ são enriquecidos em relação à água do mar. A pequena diferença isotópica observada em relação ao $\delta^{18}O$ padrão não permite conclusões definitivas sobre a formação desses dolomitos; entre as possibilidades estão o neomorfismo de dolomitos pré-existentes tardiamente neomorfizados e afetados por fluidos ricos em Sr, ou formação durante soterramento a partir de fluidos enriquecidos em Sr. Os cristais de dolomita cortam estilólitos indicando formação em subsuperfície.

VcCD e SD romboédrica apresentam valores semelhantes e muito depletados em $\delta^{18}O$ em relação aos demais dolomitos. Os valores de $^{87}Sr/^{86}Sr$ são semelhantes aos obtidos para MCD/CCD. Inclusões fluidas em SD sugerem temperatura de formação acima de 230°C. Por essas razões VcCD e SD são interpretadas como tendo se formado em subsuperfície, durante soterramento, por fluidos diagenéticos quentes e que apresentavam composição semelhante entre si.

VfCD cimenta fragmentos de brechas, mas age também como sedimento detrítico, apresentando laminação e às vezes gradação normal. Os valores de $\delta^{18}O$ são anomalos em relação aos outros cimentos e mais próximos da presumível composição isotópica da água do mar, mas não os valores de $^{87}Sr/^{86}Sr$, que são enriquecidos. Também não existe feições de campo ou diagenéticas que sugiram formação diretamente a partir da água do mar. Por essas razões VfCD é interpretado como resultando de desagregação química ou quimicamente induzida por fluidos quentes (warm brines). VfCD é muito semelhante aos denominados "dolomitos arenosos" depositados em cavernas e relacionados à atividade hidrotermal em outros depósitos minerais semelhantes.

Todas as dolomitas descritas ocorrem no nível de dolomito brechado que hospeda as mineralizações. Feições relacionadas a dissolução meteórica são raras, pequenas e preenchidas apenas com sedimento fino dolomitizado; cavidades relacionadas ao nível brechado são preenchidas além das fases descritas por sulfetos, LCC, fluorita e betumem. Portanto, as feições de dissolução e o nível brechado são consideradas como tendo se desenvolvido em subsuperfície, a partir de fluidos quentes e não guardam qualquer relação com possíveis descontinuidades da bacia.

As brechas mineralizadas são interpretadas como resultantes da ação seletiva de fluidos mineralizantes sobre um nível de brecha pré-existente. A mineralização é por isso considerada como epigenética e hidrotermal.

A idade das mineralizações é um problema em aberto; se estiver relacionado à compressão ocorrida no Ciclo Brasiliano, a idade estará compreendida entre 590-600Ma e 530Ma, sendo portanto neoproterozóica. Caso esteja relacionada a tectônica distensiva atuante na região, pode ser até de idade fanerozóica.

Os controles metalogenéticos, estão relacionados em primeira instância a fatores tectônicos e estruturais (fora do escopo da tese). No âmbito da bacia sedimentar, o principal controle metalogenético são unidades porosas e permeáveis que atuam como conduto para as soluções dolomitizantes e mineralizantes; unidades permeáveis são limitadas por fácies impermeáveis, que impedem a circulação dos fluidos (aquitardes). Níveis porosos são representados especialmente pelas unidades que compõem os membros 6 e 4; são eles também os mais afetados por dissolução/colapso gerando o extenso nível regional de brechas. Unidades que limitam a circulação dos fluidos e atuam como selantes são a parte superior, não brechada do membro 7, e na porção inferior, as unidades lamosas do membro 3. Unidades de granulação mais grossa são afetados de modo mais intenso por brechas de dissolução /colapso e freqüentemente são mineralizadas.

Durante o soterramento, as unidades permeáveis atuaram como condutos para fluidos aquecidos responsáveis pela dolomitização, brechação e mineralização.

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ABSTRACT

This study is designed to investigate the relationship between Zn/Ag mineral deposits emplacement and the host rock, dolostones of the Sete Lagoas Formation, (Bambuí Group) in the Januária region, MG. The definition of the timing and possible origin of the massive dolomitization and dissolution/collapse brecciation is of primary importance to understand the evolution of carbonate rocks and define the relationship between carbonate sedimentation, diagenetic processes and the emplacement of mineral deposits. The recognition of unconformities and their relationship with regional, large-scale brecciation is also envisaged. In order to attain these objectives, a regional and detailled mapping was done. In this research, the Sete Lagoas Formation is informally divided into seven members, grouped into three main shallowing-upwards successions, named basal intermediate and upper. The basal succession consists of the argillaceous lime mudstone member 1(basal), and calcirudite member 2, and are interpreted as recording a prograding interval deposited on a low-energy platform or shallow shelf cutted by tidal channels and sporadically affected by storms. The intermediate succession comprises the dolomitic calcarenite member 3, dolostone member 4, stromatolite dolostone member 5, ooid-intraclast dolostone member 6, and the lowermost unit (7A) of the dolomudstone member 7. Its overall interpretation is that it represents a shallowing-upwards succession from muddy to sandier sediments deposited in offshore through a sandier shoreface with stromatolite reefal barrier, lagoonal and beach to tidal flat environments; subaerial exposure of the carbonate platform ended the intermediate shallowing-upwards succession. An unconformity assumed by some authors as developed above the ooid-intraclast dolostone member 6 (the pink dolostone) is not recognized in this research. The uppermost succession, made up of small peritidal cycles, is interpreted as representing a series of prograding tidal flat successions that record low-energy environments. The three main succession are interpreted as a parasequence set of a progradational stacking pattern. The increase in pelitic sediments upwards in the overlying Serra de Santa Helena shut down the carbonate platform.

Regarding diagenesis, the carbonate rocks of the Sete Lagoas Formation has undergone diagenetic alteration in subaerial, submarine and subsurface environments. Diagenetic features of subaerial diagenesis include desiccation cracks, tepees, vadose cements and small-scale dissolution vugs; submarine environment is represented by isopachous fibrous cement around allochems suggesting beachrock cementation. Subsurface diagenesis resulted in the most important modifications in the carbonate rocks and includes, among others, compaction, blocky sparry calcite, hydrothermal dissolution, dolomitization, sulfide and silicate ore minerals, late-stage coarse-crystalline calcite, fluorite and bitumen.

The dolostones hosting mineral deposits are made up of replacement dolomites and cements and are strongly afected by dissolution/collapse brecciation. The main dolomite types recognized in the Januária region related to mineral deposits, are in paragenetic sequence: microcrystalline (McCD), medium-crystalline (MCD), coarse-crystalline (CCD), very-coasecrystalline (VcCD), saddle (SD) and very finelly crystalline. McCD represent early, penecontemporaneous replacement dolomites and MCD/CCD, late replacement dolomites. Very coarse-crystalline dolomite (VcCD), saddle dolomite (SD) and very finely crystalline dolomite (VfCD) are dolomite cements.

McCD occurs mostly in sediments of the dolomudstone member 7 and stromatolites/fine sediments of the member 5. MCD/CCD are widespread and affect mostly the dolostone and ooid-intraclast dolostone member (4 and 6). VcCD and SD are closely associated with each other and occur in cavities and fractures in MCD/CCD, crosscut the limits between the

members 6 and 7 what indicate they are formed later than the presumed unconformity developed above member 6, as already mentioned. SD occurs in rhombohedral (pink or pale gray saddle dolomite) and saddle forms (white saddle dolomite); white SD is later than rhombohedral ones. VfCD is restricted to dissolution/collapse breccia layer and affects the all above described dolomites, except possibly the white SD.

The dolomites and late-stage coarse-crystalline calcite (LCC) were analysed for C/O isotopes, as well as to Sr isotopes. Samples of the basal limestones were analysed in order to have bench markers representing the estimated isotopic signature of the Neoproterozoic seawater of the Sete Lagoas Formation and these values will be used as a reference to determine post-depositional diagenetic changes. The Sr isotopic composition suggests sedimentation of the Bambuí Group started at around 590 to 600Ma.

The obtained $\delta^{18}O$ values (PDB) inferred to represent the composition of seawater or slighly modified seawater during deposition of the Sete Lagoas Formation.range from
–6.11 to –6.56‰ (mean = -6.39) and $\delta^{13}C$ range from 0.26 to 0.58‰ (mean = 0,42‰). The $^{87}Sr/^{86}Sr$ ratio of seawater during deposition of the Sete Lagoas Formation is estimated to be between 0.7076 and 0.7079 based on micritic limestones at the base of the section.

McCD: $\delta^{18}O$ values is within the range of values for dolomites that would precipitated from Sete Lagoas Formation seawater, or slighly modified seawater. The $^{87}Sr/^{86}Sr$ ratios range are slighly higher than the estimated original isotopic signature of the Neoproterozoic Sete Lagoas Formation seawater, suggesting that their original isotopic signature were partly modified by later diagenetic fluids.

MCD/CCD: $\delta^{18}O$ values are slighly depleted compared to the Neoproterozoic seawater. The $^{87}Sr/^{86}Sr$ ratios are more radiogenic than the estimated seawater of the Sete Lagoas Formation. The present data do not provide an unequivocal conclusion concerning the origin of MCD/CCD; these dolomites could result from previous dolomites late affected by neomorphism and diagenetic fluids Sr-rich or formed under burial conditions by Sr-rich fluids. MCD/CCD postdate stylolites suggesting that dolomitization occured during burial.,VcCD/SD show similar $\delta^{18}O$ values, the most depleted ones. $^{87}Sr/^{86}$ Sr ration are similar to MCD/CCD, thus more radiogenic than the estimated seawater. Fluid inclusion measurements in SD suggest entrapment temperature above 231°C. Thus VcCD/SD are interpreted as being formed in subsurface during burial by warm diagenetic fluids of similar chemical composition. VfCD cements all kind of breccia fragments but also act as internal sediment displaying lamination and/or normal grading. Locally is closely related to mineralization. The $\delta^{18}O$ values is within the range of Sete Lagoas Formation seawater, however the $^{87}Sr/^{86}Sr$ values are not compatible with the estimated Neoproterozoic seawater. There is no diagenetic feature or field relationship could suggest formation of VfCD directly from seawater. Thus, VfCD is interpreted as resulting from chemical or chemically induced mechanical disaggregation by warm brines. VfCD is similar to the named "sanded dolomites" deposited in internal cavities and related to hydrothermal activity.

All described dolomites occur in the brecciated dolostone level making a stratigraphic level in the Januária region, as well as in the middle São Francisco valley, and resulting from dissolution/collapse brecciation. This study indicate that dissolution occurred mostly in subsurface; dissolution related to subaerial exposure are minor and differ from subsurface in at least three main aspects: dissolution vugs related to meteoric waters are small, areally restricted and the infilling material are only fine dolomitized sediment. Dissolution features considered as resulting from subsurface warm fluids, are widespread, the filling material includes VfCD, SD, VfCD, sulfide, LCC, fluorite and bitumen, and dissolution/brecciation crosscut the hypothetical unconformity of previous authors developed above the member 6. Thus, most of the dissolution and breccias resulted from action of hydrothermal fluids during burial, and ore-bearing dissolutin/collapse breccias are interpreted to be the result from selective sulfide replacement of pre-ore collapse breccia. Mineralization is thus epigenetic, resulting from the action of subsurface warm fluids, interpreted as hydrothermal.

The timing of mineralization is one of the unsolved problems. As dolomitization and the emplacement of ore minerals took place during burial of the sediments, considering the compressional model, the Januária mineral deposit could be related to the evolution of the Brasiliano Cycle and thus restricted to the Neoproterozoic. However, if emplacement of mineral deposits is related to extensional tectonics, the timing of mineralization need not be restricted to the Neoproterozoic and could be Phanerozoic in age.

The main metallogenic control is tectonics, that provide the driving forces responsible for fluid flow over large areas. Faults and fractures are the main conduits for the ascending flow in a basin. Within the basin, fluid flow is controlled also by porosity and permeability of sedimentary units. Thus, the interaction of fauts with permeable sedimentary units and unconformities of the basin define the regional pattern of related dolomitization and dissolution/collapse breccia development. This same association, depending on the availability of the sulphur, also controls ore emplacement. Thus, the first major control in the study area related to the carbonate sediments is the distribution of strata with contrasting permeabilities. The porous units are lithofacies of the dolostone and ooid-intraclast dolostone members (4 and 6), limited by non-porous, impermeable ones (aquitards); the lowermost unit to act as aquitards was the basal fine carbonate of the dolomitic calcarenite member 3 and the uppermost unit was lithologies of the dolomudstone member 7. These aquitards controlled dolomitization, dissolution/collapse brecciation and ore mineral deposits. During burial, the permeable units acted as conduits for warm, hydrothermal dolomitizing and mineralizing fluids.

PREFÁCIO

Antes do desenvolvimento deste projeto de pesquisa, os carbonatos do Grupo Bambuí pertencentes à Formação Sete Lagoas, na região de Januária-MG, não haviam sido estudados de modo sistemático do ponto de vista sedimentológico, diagenético, e não havia correlação entre esses processos e os depósitos minerais de Zn/Ag. Os estudos de estratigrafia regional e sedimentologia abrem novas possibilidades para interpretações paleogeográficas e evolução da bacia do São Francisco. Análises geoquímicas de C/O e Sr contribuem decisivamente para os estudos diagenéticos dos dolomitos brechados, hospedeiros das mineralizações. Os novos dados e suas interpretações têm aplicação imediata em termos de estudos diagenéticos em outras áres da bacia. As maiores contribuições deste estudo são :

1: A definição da estratigradia e sedimentologia da região de Januária foi estabelecida. Não existem evidencias que permitam afirmar que os dolomitos róseos, pertencentes aos dolomitos oolíticos/intraclásticos, foram expostos com desenvolvimento de um carst meteórico. Dolomitos são a principal litologia e hospedam os depósitos minerais.

2: A sequencia paragenética dos dolomitos foi estabelecida.

3: Foram identificados.cinco tipos de dolomitos relacionados aos depósitos minerais.

A origem e *timing* desses dolomitos foi estabelecida baseado em suas distribuições espaciais, nas relações que apresentam entre si, características petrográficas, paragenese diagenética e assinaturas geoquímicas.

4: O papel das dissoluções relacionadas a processos meteóricos versus dissolução hidrotermal é analisada com relação aos depósitos minerais. Processos meteóricos causaram apenas pequenas e localizadas feições de dissolução, mas as brechas e cavidades associadas que são de extensão regional e hospedam as mineralizações resultaram da ação de fluidos hidrotermais durante o soterramento. Este resultado tem importante implicação para a exploração mineral. Horizontes brechados podem ainda constituir importantes reservatórios de gás.

5: A idade das mineralizações é desconhecida, mas sua colocação certamente ocorreu em profundidade, durante o soterramento dos carbonatos.

6: Este estudo sugere ainda que em bacias sedimentares, feições diagenéticas tais como dissolução hidrotermal e dolomitização podem estar relacionadas e serem controladas em parte pela evolução da bacia, mas os elementos tectonicos e o regime tectonico são de fundamental importancia. A evolução da bacia sedimentar é responsável pela geração de descontinuidades que em associação com os elementos estruturais constituem os canais por onde irão fluir as soluções dolomitizantes e mineralizantes. Descontinuidades sedimentares neste caso estão relacionadas a grandes diferenças em permeabilidade e porosidade entre unidades sedimentares, constituindo assim *traps* estratigráficos. Posterior dolomitização transforma os sedimentos originais, mas mantém as unidades de contrastantes permeabilidade.

7: O motor, responsável pelo sistema hidrodinamico que iniciou a movimentação de fluido em larga escala ao longo de condutos preferenciais e que foi responsável pela dolomitização e colocação de depósitos minerais não está bem definido: um sistema compressivo relacionado à tectonica brasiliana seria uma possibilidade. Outra hipótese relacionaria a movimentação dos fluidos à deformação extensional; neste caso, as mineralizações não seriam necessariamente neoproterozóicas.

8: Resumindo, a colocação dos depósitos minerais foi certamente controlada por descontinuidades relacionadas ao desenvolvimento da bacia sedimentar a sistemas de falhas, ativos desde o princípio da sedimentação carbonática. Falhas atuaram como condutos para o fluxo de fluidos responsáveis pela dolomitização, desenvolvimento de brechas de dissolução e colapso e mineralizações.

9: Antes do término da tese parte dos resultados serão submetidos para publicação. A informação para essas publicações estão em sua maior parte contidas no corpo da tese.

Os artigos a serem submetidos para publicação são os seguintes:

- **Sedimentology and cyclicity of the Sete Lagoas Formation in the region of the middle São Francisco River and stratigraphic correlations of the lower part of Bambuí Group across the São Francisco Basin.**
- **Petrography and diagenesis of the dolostone level in the region of the middle São Francisco valley region; implications on the formation of dissolution vugs and breccias hosting base-metal mineral deposits.**
- **Dolomitization in the middle São Francisco region: possible models. Preliminar correlations with other dolostones in the basin.**
- **Hydrotermal origin of dissolution vugs and breccias in Januária region; relashionship with the mineral deposits.**
- **Isotopic signature of carbonate rocks of the Sete Lagoas Formation.**
- **Strontium isotopes of the Sete Lagoas Formation as an instrument supporting age definition of the Bambuí Group in association with paleontologic record.**

PREFACE

CONTRIBUTION TO ORIGINAL KNOWLEDGE

Prior to this research project, the Januária region was devoid of sedimentological and diagenetic studies. Interpretations were based mainly on very general, regional knowledge. This is the first regional project that systematically studied the sedimentology, diagenesis and geochemistry of the sediments and associated mineralized areas. The regional stratigraphy and sedimentology offer new interpretations on the paleogeography and basin evolution in that area. The geochemical result offers new analysis related to the diagenesis of the brecciated dolostone, host of the mineral deposit. New data and their interpretations have immediate applications in terms of the diagenetic studies in other parts of the São Francisco Basin. The major contributions of this study can be summarized as follows:

1. The stratigraphy and cyclicity of the Sete Lagoas Formation at the Januária region is defined; no clear evidence of subaerial exposure responsible for unconformity or meteoric karst development was found over the ooid-intraclast dolostone member (pink dolostone) was found; dolostones are the dominant lithology and host the mineral deposits.
2. The diagenetic paragenesis of dolostones is established
3. Five types of dolomites related to mineral deposits were identified. The origin and timing of these dolomites are established on the basis of their distinctive spatial distribution, cross cutting relationships, petrographic characteristics, diagenetic paragenesis and geochemical signatures.
4. The role of meteoric solutions versus hydrotermal dissolution is differentiated in the mineral deposits. Meteoric waters caused only minor dissolution on the top of a stromatolitic reef barrier, the dissolution vugs and breccias resulting from action of hydrothermal fluids during burial. This result has important implications for mineral exploration. Mineral deposits hosted in brecciated dolostone are not always related to unconformity or meteoric karst and mineralization can occur in any available vugs and/or fractures whatever their origin. Brecciated horizons may also constitute important gas reservoirs.
5. The age of mineralization is unknown, but its emplacement certainly occurs during deep burial of the sediments or postdates this event. Fluid inclusions containing oil in sphalerite indicate deposition concomitantly with the oil onset.
6. This study suggests that diagenetic features in a sedimentary basin, such as hydrothermal dissolution and dolomitization, can be related and controlled in some way by the evolution of the basin but tectonic elements as fault systems and the tectonic regime in itself are also of fundamental importance. The evolution of the basin is responsible for discontinuities that in association of the structural elements made up the conduit system responsible for the flowing of warm migrating brines. Sedimentary descontinuity in that case is related to strong differences in permeability and porosity between grainstones to packstones covered in most of the area by muddy carbonate defining thus a stratigraphic trap. Later, dolomitization transformed the original sediment, keeping the packages of dolostone with contrasting permeability.

7. The motor, responsible for the development of the hydrodynamic system that initiates large-scale fluid flow which played a role in dolomitization and mineralization along preferential conduits is doubtfull: a compressive system related to tectonic thrusting and related to fold belts surrounding the São Francisco Craton (Brasiliano Cycle) is a possibility. Another hypothesis would be related to a extensional deformation involving overpressuring and episodic discharge during fault reactivation; in this case, mineralization is not necessarily Neoproterozoic in age.
8. Summarizing, the emplacement of mineral deposit was mainly controlled by discontinuities related to basin development and fault systems, active since the begining of the basin development. Faults have acted as conduit for fluid flow responsible for dolomitization, dissolution/collapse breccia and mineralization.
9. Prior to the completion of this thesis, part of the research results will be submitted for publication. The information contained in these papers and abstracts is integrated into the body of the thesis.

PAPERS:

- **Sedimentology and cyclicity of the Sete Lagoas Formation in the region of the middle São Francisco River and stratigraphic correlations of the lower part of Bambuí Group across the São Francisco Basin.**
- **Petrography and diagenesis of the dolostone level in the region of the middle São Francisco valley region; implications on the formation of dissolution vugs and breccias hosting base-metal mineral deposits.**
- **Dolomitization in the middle São Francisco region: possible models. Preliminar correlations with other dolostones in the basin.**
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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

This study was designed to define some of the metallogenic controls of Zn/Ag mineral deposits hosted in dolostones of the Sete Lagoas Formation (Bambuí Group) in the Januária region. It intents to investigate the relationship between mineral deposits emplacement, diagenetic processes and the regional evolution of the sedimentary basin in view to define if unconformities could act as metallogenic control.

The definition of the timing and possible origin of the massive dolomitization is of primary importance to understand the diagenetic evolution of the carbonate rocks hosting the mineral deposits. This knowledge allows us to define the relationship between carbonate sedimentation, diagenetic processes and the emplacement of mineral deposits.

As mineralization is always related to brecciated dolostones, the investigation of the origin of the breccias was also of main importance. Breccias are supposed to be of hydrothermal origin or related to subaerial exposure.

The role of tectonics affecting the evolution of the basin as well as the emplacement of the mineral deposits, though considered, is not the main scope of the thesis.

Thus, the main objectives of this research are:

1. To describe the main sedimentological features of the carbonate rocks; identification of unconformities. Definition of the cyclicity on the sedimentary succession and the relationship between sedimentary cycles, unconformities and the paleogeographic evolution of the study area.

2. The characterization of the diagenetic features of the carbonate rocks, with emphasis on the dolomitization and its relationship with mineral deposits.

3. The study and documentation of the diagenetic features across a prior suggested unconformity in the area, includding: i) the relationship, if any, between subaerial dissolution and the possible unconformity, and ii) the types and spatial distribution of dolomites above and below the unconformity.

4. A systematic study of a series of geological sections aiming also at delineating the spatial distribution of the dolomites.

5. Discussion of the possible relashionship between tectonic events and the emplacement of the mineralizations.

The following techniques and geochemical analysis are used in this study to constrain compositions and possible sources of the dolomitizing fluids for different types of dolomites: i) staining, ii) cathodoluminescence microscopy, iii) Oxigen and Carbon isotopes, iv) Strontium isotopes and v) fluid inclusions.

Considering both geological and geochemical data, the composition and source(s) of the dolomitizing fluids are interpreted. The result of this research should define the conditions under which some dolomites of the Bambuí Group were formed. Since dolostones are the host rocks for mineral deposits in the Januária region, this study places additional limits on the process of mineralization, especially the origin(s) of dissolution features and the relative timing of mineralization.

1.2 LOCATION OF THE STUDY AREA

The study area is located in middle São Francisco valley region, northwest of Minas Gerais State in the left margin of the São Francisco valley between 15^0 20'S/ 15^0 45' S latitude and 44^0 00'W/44^0 45'W longitude (Figure 1.1). Januária is the main regional town, whereas Tejuco and Pandeiros are the main villages. Others localities as Itacarambi and Fabião I and II are located about a hundred kilometers north of Januária.

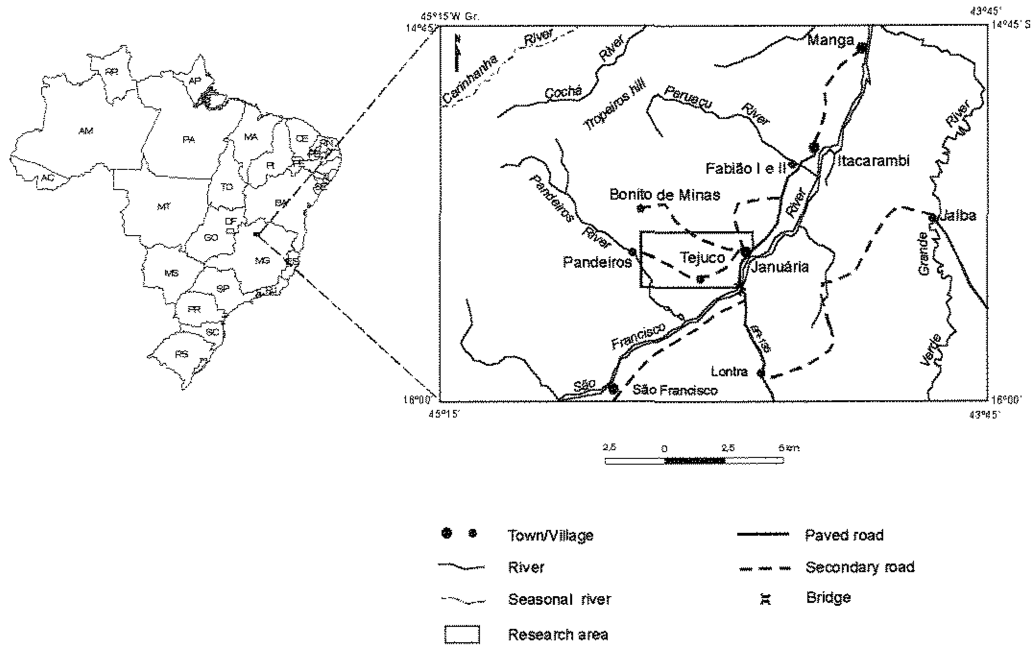


Figure 1.1. Location map.

Januária can be reached by plane or by paved two-lane roadways. Local roads are mainly two-lane rural roadways.

1.3 METHODS

Januária region was devoid of both regional and local detailled mapping; for this reason 7 geological sections were systematically described and sampled in barren and mineralized areas in order to compare and contrast them. Where possible, the spatial distribution of the dolostones has been mapped with emphasys on the brecciated dolostone. Other 3 sections were only partly described due to access problems.

The whole of the Bambuí Group outcropping at the Januária region was described. The Sete Lagoas Formation (Costa and Branco 1961) to which belong the main studied strata is the dominant unit in the region whereas the Serra de Santa Helena Formation was observed only locally. The described sections are located in Figure 1.2.

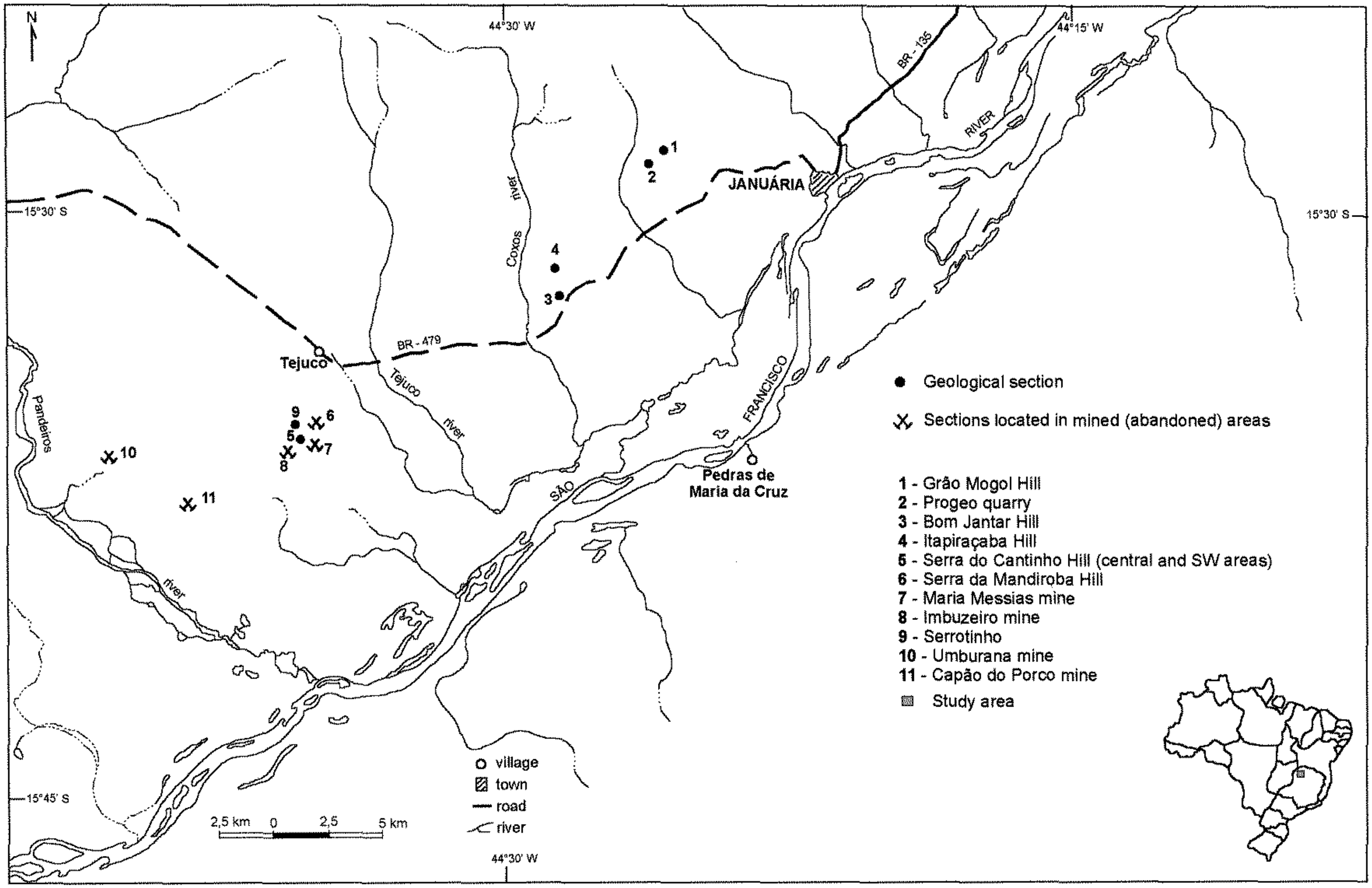


Figure 1.2. Location of described geological sections.

Sections are vertical and composite, and were described at scale of 1:50 or 1:100; thicknesses of the strata were mostly measured though also estimated in a few cases.

Approximately 250 thin sections were studied. All thin sections were stained with alizarin-red S and potassium ferrocyanide following the procedure outlined by Dickson (1965). Of these, 80 thin sections were observed under cathodoluminescence microscope.

Representative ore minerals and dolomite samples were also studied under scanning eletron microscope (SEM) at the Center of Mineral Technology – CETEM, by Dr. Arnaldo Alcover.

Powdered carbonate microsamples ranging from 0.3 to 0.5 mg were drilled from slabs using dental drill and tungsten carbide bits for carbon and oxigen microanalysis as well as for Sr isotopes analysis.

$\delta^{18}O_{PDB}$ and $\delta^{13}C_{PDB}$ were analyzed at the G. G. Hatch Laboratories, University of Ottawa, Canada, using the chemical separation of Al-Aasm (1990) where necessary.

Sr isotopes were analysed at the Federal University of Pará. Sr was leached from leachage of dolomite and calcite samples using standard cation exchange techniques with 2,5N HCL. The Sr isotopic analyses were performed on a VG Isomass 54E at the Laboratory of Isotopic Geology (PARA-ISO), of the Federal University of Pará. The samples were loaded as $SrCl_2$ on a W filament; an activator Ta rich was introduced to improve the accuracy of measurements. The error is two sigma from the mean for the internal precision of a single analysis. The average value of the NBS987 standard during the course of the study was 0,710307.

Fluid inclusions from doubly polished thin sections were analysed at the Department of Earth and Planetary Science, McGill University, Canada, using a U.S.G.S. designed heating-cooling stage.

1.4 PREVIOUS STUDIES

The Januária region is located in the stable portion of the São Francisco Craton (Alkmin et al. 1993). As some features recognized in Januária are regionally widespread and considered by some authors as controlling mineralization, data from outside the study area will be presented here.

The main studies are those of Robertson (1963), Cassedanne (1972), Dardenne (1979), Lopes (1979), Rabelo (1981) and Abreu-Lima (1997). The location of stratigraphic sections and their correlations are shown in Figure 1.3.

The most complete local study in the Januária region was done by Robertson (1963) studying lead-zinc mineralization. The author described limestones and dolomites but did not perform any petrographic studies. Mineralization is related to a regional horizon named black weathering dolomite and considered as hydrothermal, epigenetic, showing similarity with MVT deposits.

Cassedanne (1972) described in a general way the dolostone hosting mineralization and most of the mineral deposits. The mineralogy of ore and gangue was studied based on macroscopic and microscopic petrographic studies. For more details see Chapter 3.

Abreu Lima (1997) studied the basal carbonate horizon of the Bambuí Group, the Sete Lagoas Formation, based on diamond drill cores and on outcrops. The study area emcompasses all the middle São Francisco valley region and the author considers the Sete Lagoas Formation as composing a single shallowing upward cycle.

Studying an area located one hundred kilometers north of Januária, Dardenne (1979) defined the general stratigraphy of the region: two carbonate horizons separated by a pelitic "sequence" (Serra de Santa Helena Formation). The lower carbonate horizon is the Sete Lagoas Formation and the uppermost one is the Lagoa do Jacaré Formation, renamed by the author as Januária and Nhandutiba formations, respectively.

Dardenne (*op. cit.*) divided the lower carbonate horizon into four main units; the lower part of the basal unit (Unit B) do not outcrop in the research area where the lowermost outcrop can be correlated to the upper part of the basal unit; units C to E are well exposed. Sediments of Unit D (pink dolostone) are supposed to have been subaerially exposed with unconformity development. Regarding dolomitization, Dardenne (1979) considers the fine dolomite of Unit E as early diagenetic; the coarse dolomite would be epigenetic but strictly related to the early dolomite stratigraphically above.

Mineralization would be related to a subaerial exposure surface (unconformity); metal concentrations would be syndiagenetic, related to an evaporitic environment. Later fluids moving along the unconformity and faults/fractures induced dissolution with development of the collapse breccia responsible for the fluorite emplacement.

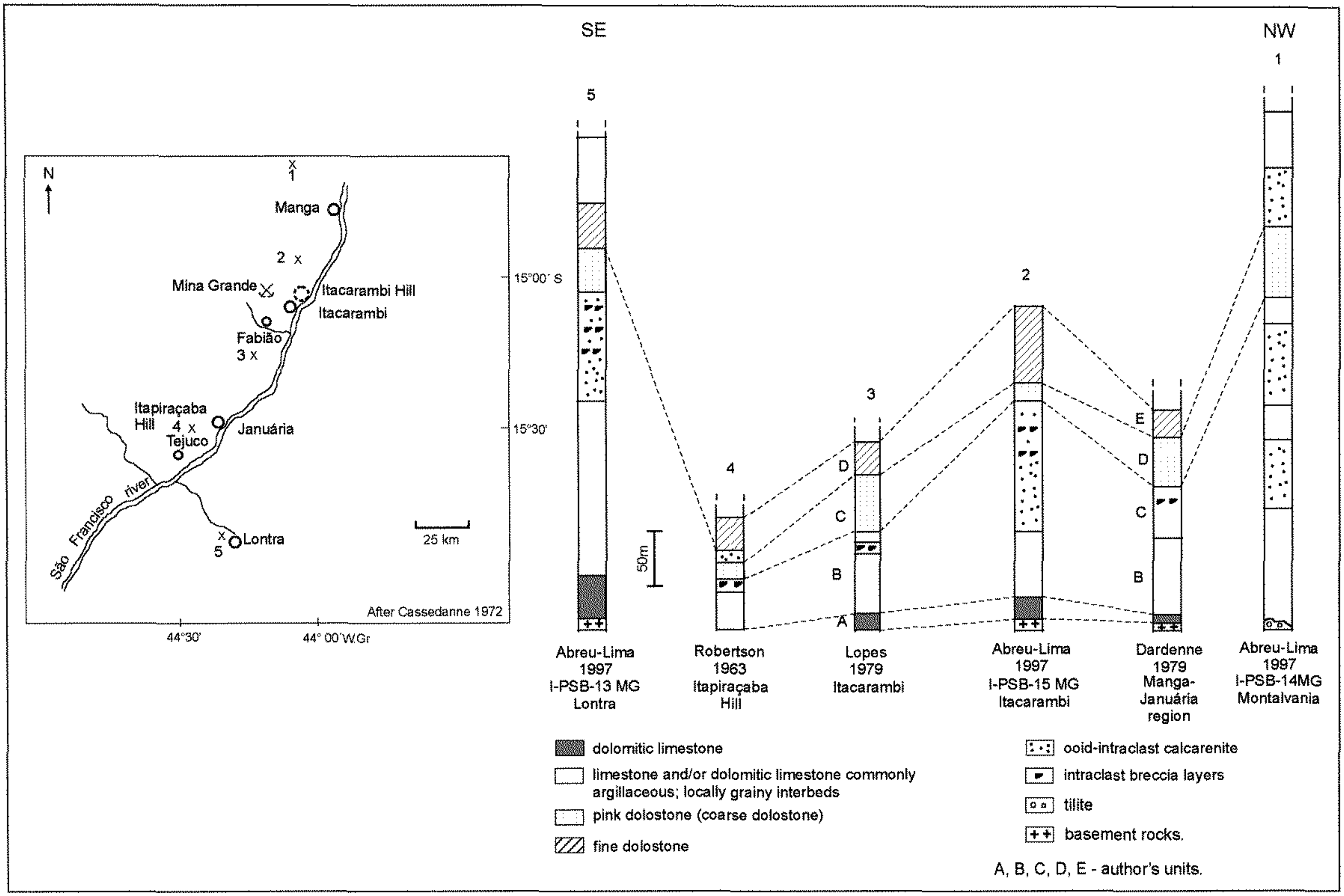


Figure 1.3. Stratigraphic correlation of the Sete Lagoas Formation based on previous works.

Lopes (1979) has studied the mineralization at Itacarambi (160 km north of Januária) and considers that after peneplanation of the basement rock, blocks subsiding differently exerted important control on sedimentation. A northwest and a northeast fault system are recognized, the latter along São Francisco River (Guimarães 1942).

The Sete Lagoas Formation (basal) is subdivided into four stratigraphic units. The lower unit (A), made up of dolomitic limestones with desiccation cracks, is followed by Unit B, composed of limestones with thin pelitic and breccia layer interbeds; chert lenses/nodules are common. Unit C, stratigraphycally above, is the pink dolostone (Unit D of Dardenne 1979) having breccias at the top; some breccia fragments are of Unit D, stratigraphycally above. This upper unit, D, is composed of fine dolostone and exhibits desiccation features. Units B, C and D are recognized in the Januária region.

Unit A is considered as representing supratidal environment and breccia of Unit B are related to earthquaker. Dolostones of Unit D would have been deposited in shallow waters with fine dolostones representing shoreline or supratidal deposits.

The author considers that a regional meteoric karst resulting from a subaerial exposure would have been developed on the top of the Unit C, the pink dolostone.

Dolomites are interpreted as resulting from environmental changes and the paragenetic sequence is not clear.

Metals would be concentrated syndiagenetically around the unconformity related to the subaerial exposure with later remobilization by diagenetic and tectonic processes.

Rabelo (1981) considers the Bambuí sediments of the Januária-Itacarambi district as "transgressive over gneisses and granites of the São Francisco craton". The paleotopography of the basement would control the distribution of the facies. Normal faults transecting the area in the NNW-SSW direction are considered of some importance and would reflect basement movements which "continued throughout and long after the Bambuí deposition". One of these faults located near the Tejuco village is identified as a magnetic anomaly. The Sete Lagoas Formation is divided into five packages from base to the top: base argillaceous limestone, marls and well-bedded limestones developed in subtidal environment. Stratigraphycally above, intraformational breccia with mudcracks would represent intertidal to supratidal environment and the pink saccharoidal dolomite with cross-bedding intertidal environment. A subaerial exposure surface separates the pink dolomite from the microcrystalline dolomite with planar stromatolite (top of the succession), representing a shallow-subtidal to intertidal environment. Capping the section, marls of the Serra de Santa Helena Formation.

Mineral deposits are considered as related to a subaerial exposure surface developed over intertidal sediments. The sequence of events would be: deposition of the sediments on intertidal environment, minor uplift, dolomitization, karst development, mineralization in the karstic breccia followed by subsidence and deposition of microcrystalline dolomite under shallow-subtidal to intertidal conditions. Mineral deposits would be of MVT but the author is not conclusive concerning the origin of mineralization.

1.5 ORGANIZATION OF THE THESIS

By benefit of the thesis organization and interpretation of the data, there is some overlap of material covered in the separate chapters.

The objectives of this study, previous works and methods are discussed in Chapter 1.

The geology, regional correlations and stratigraphy of Bambuí Group are summarized in Chapter 2, which also provides background information for the following chapters.

Mineralization in the Januária region is presented in Chapter 3.

The stratigraphy and particularly the sedimentology of Sete Lagoas Formation in the study area are discussed in Chapter 4; this chapter furnishes the basic data for paleoenvironmental interpretations, and the definition of unconformities and cyclicity of the carbonate rocks. Data presented in Chapter 4 also provide the basic framework for studies concerning diagenesis and mineralization.

Diagenetic paragenesis of the studied carbonate rocks is discussed in Chapter 5.

The origin of various types of dolomites is discussed in Chapter 6, based on evidence from petrography, spatial distribution, diagenetic paragenesis, geochemistry, and secondarily on fluid inclusions.

The origin and dissolution vugs and breccias that host the mineral deposits has been controversial for a long time. The evidence for hydrothermal dissolution is discussed in Chapter 7.

The possible timing of dolomitization and the possible age of the mineralization are discussed in Chapter 8.

Chapter 9 provides a summary and the conclusions of this study.

CHAPTER 2

THE BAMBUÍ GROUP

2.1 GEOLOGIC SETTING

The Bambuí Group is part of the São Francisco Basin, located at center-eastern region of Brazil (Fig. 2.1), and represents a platform cover developed over the São Francisco Craton (Almeida 1977; Alkmin et al. 1993). The São Francisco Craton is surrounded by fold belts, named Brasilia, Rio Preto, Riacho do Pontal, Sergipano and Araçuaí; these belts are related to the Brasiliano Cycle.

The evolution of the São Francisco Craton started in the Archean and ended at the close of the Mesoproterozoic. The São Francisco Craton is part of the Gondwana Neoproterozoic supercontinent, formed by agglutination of continental masses which were envolved in multiples and successive collisions. Tectonics started at about 750 Ma ago, but developed mainly between 650 and 530 Ma, coinciding with the main orogenic phases of the Brasiliano-Pan African Cycle (Cordani et al. 2000).

The Bambuí Group outcrops over more than 200 000 square km over parts of the Minas Gerais, Goiás and Bahia states. To the west and separated from the Bambuí sediments by Mesoproterozoic metasediments of the Espinhaço Supergroup, there is a large area of carbonate rocks belonging to the Una Group that is correlated with the Bambuí Group on the basis of similar stratigraphy and paleomagnetic data.

Strata of the Sete Lagoas Formation in the lower part of the Bambuí Group, the main subject of this study, can be correlated across the basin. Almost 800 km away from Januária, a similar succession occurs in Arcos, in the southwest part of the basin (Nobre-Lopes 1995).

In this connection it is important to say that the sedimentary succession of the Bambuí Group is not homogeneous; the extent, geometry and thickness of facies and members are highly variable and formations can pinch out or are missing in some places.

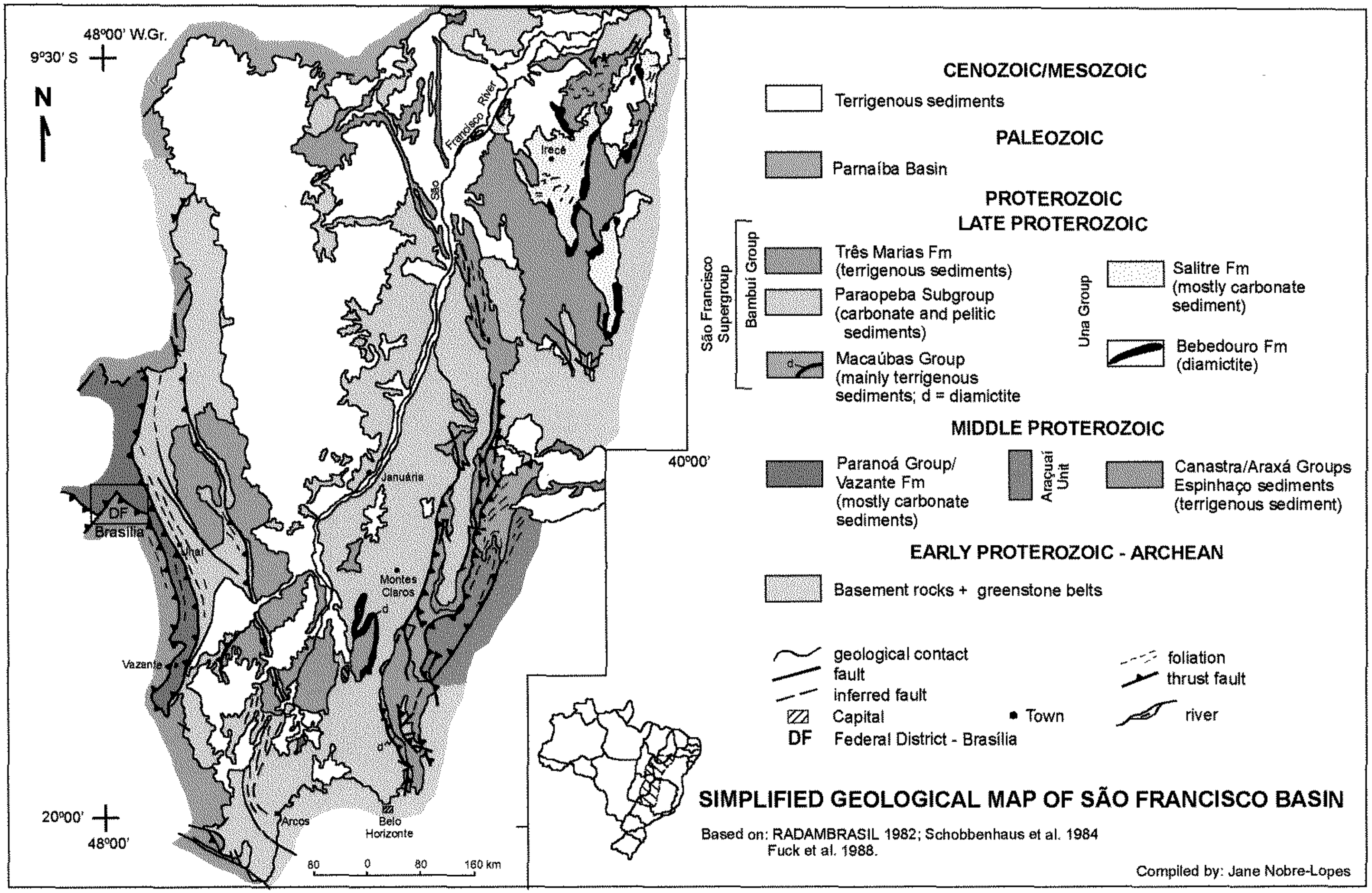


Figure 2.1. Simplified geological map of the São Francisco Basin.

During Mesozoic time most of the Bambuí Group was subaerially exposed, eroded and covered by hundred of meters of Mesozoic siliciclastic sediments of the Urucuia Formation. The Urucuia sandstones are more than 2km thick, about 100km west of Januária, in the central part of the continental Mesozoic basin.

There are no data concerning sedimentation during the span of time between the Neoproterozoic and the Mesozoic.

Regarding tectonic aspects, along the above mentioned fold belts sediments of Bambuí Group are strongly deformed; farther away from the thrust belts gradually strata become horizontal and are considered as being deposited in the stable portion of the craton.

In this stable area tectonic features are mainly normal faults with vertical movement of blocks. Important and well defined structural elements are two paralel and elongated NNE-SSW gravimetric anomalies (Lesquer et al. 1981) which represent uplifted blocks of the basement buried under Neoproterozoic sediments and related to synsedimentary fractures in the basement. Another important system of faults trends NNW-SSE (Lopes 1979; Rabelo and Santos 1979; Roccio 2000 *unpublished*). These main fault systems were active during sedimentation of the Sete Lagoas Formation resulting in important differences in thickness across these structures.

A simplified map of São Francisco Craton with main tectonic domains of Bambuí and Una Group are presented in the Figure 2.2.

The evolution history of the basin is not well established, the existent hypotheses are controversial as data are scarce, local, and in cases speculative. Chang et al. (1988) suggested that the São Francisco Basin could represent fold and thrust belts associated with foreland basins. Alkmin et al. (1989) considers only the upper part of the Bambuí Group as being deposited in a foreland basin during the Brasiliano Cycle. Martins-Neto et al. (2001) working on the eastern part of the craton suggest that the Bambuí sediments were deposited in a foreland basin resulting from flexural movements by tectonic load in Brasiliano times.

There are no data concerning depositional centers in the basin. The complete thickness was obtained in a single drill hole located near Lontra village, ~60km southeast of Januária (Brandalise et al 1980) which reach basement rocks after drilling through ~700m of Bambuí sediments.

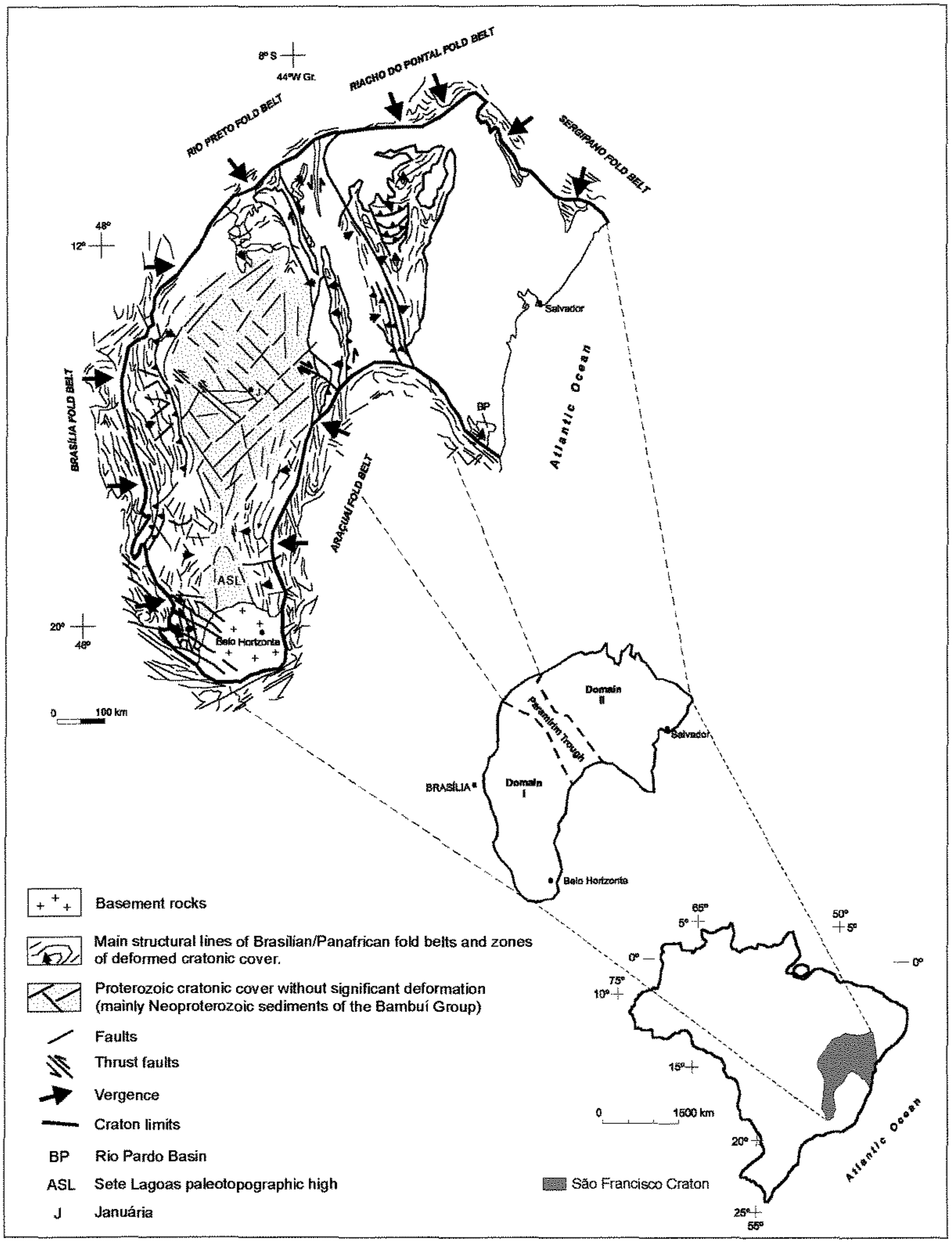


Figure 2.2. São Francisco craton structural domains (adapted from Alkmin et al. 1993; structural elements of the cratonic cover: Lesquer et al. 1981; Rocio 2000 *unpublished* and Nobre-Lopes 2000 *unpublished*).

Regarding age, the Bambuí carbonate sedimentation is interpreted to have started at ca. 1000 Ma, after a glacial episode. However the age of the group is still debated since the various isotopic dating methods give somewhat different results. K/Ar and Rb/Sr data for pelitic sediments show ages between 650 to 600 Ma (Amaral and Kawashita 1967; Parenti Couto et al. 1981; Thomaz Filho et al. 1998). Babinsky et al. (1997) considers 690 Ma as the minimum age for the Bambuí sedimentation based on Pb/Pb data from limestones. Chang et al. (1997) suggested an age of 600 Ma for the Bambuí carbonates based on $^{87}Sr/^{86}Sr$ ratios of carbonate rocks. Planktonic microfossils, ACHRITARCHAE were identified in the lower part of the Sete Lagoas Formation (Cruz and Nobre-Lopes 1992), suggesting an age between Late Riphean and Vendian; one specimen, not identified taxonomically exhibit ornaments and spines suggesting an age closer to the Precambrian-Cambrian boundary. $^{87}Sr/^{86}Sr$ ratios of basal limestones outcropping at Januária (this research) indicate deposition of the Sete Lagoas Formation starting around 590 to 600 Ma.

2.2 STRATIGRAPHY

The Bambuí Group belongs to the São Francisco Supergroup (Pflug and Renger 1973), the main unit encompassing all sediments deposited during the Brasiliano Cycle in the region under the influence of the São Francisco Craton. Rimann (1919) was the first author to use the term Bambuí to designate sediments now belonging to the Bambuí Group, but the first citations of carbonate rocks along the São Francisco valley were actually made in the 19^{th} century.

The stratigraphy of the Bambuí Group as defined by Costa and Branco (1961) is still followed, though with some revisions (Table 2.1). In this study, the stratigraphy proposed by RADAMBRASIL (1982): the Sete Lagoas Formation (basal), Serra de Santa Helena, Lagoa do Jacaré and Serra da Saudade formations comprising the Subgroup Paraopeba. The Tres Marias Formation is the uppermost unit of the Bambuí Group (see Fig. 2.1). The Sete Lagoas Formation is made up of limestones and dolostones; the Serra de Santa Helena is mainly pelitic with limestone lenses; dark limestones characterize the Lagoa do Jacaré Formation; Serra da Saudade Formation is pelitic with subordinate limestone lenses. The Tres Marias Formation is made up of immature siliciclastic sediments.

<table>
<tr><th colspan="2">COSTA and BRANCO (1961)</th><th>BARBOSA (1965)</th><th>OLIVEIRA (1967)</th><th>BRAUN (1968)</th><th>DARDENNE (1978)</th><th colspan="2">RADAMBRASIL (1982)</th></tr>
<tr><td>Members</td><td>Formations</td><td>Formations</td><td>Formations</td><td>Formations</td><td>Formations</td><td rowspan="8">Paraopeba Subgroup</td><td>Formations</td></tr>
<tr><td>Serra da Saudade</td><td rowspan="4">Paraopeba</td><td rowspan="2">Três Marias</td><td rowspan="2">Três Marias</td><td rowspan="2">Três Marias</td><td>Três Marias</td><td>Três Marias</td></tr>
<tr><td>Três Marias</td><td>Serra da Saudade</td><td>Serra da Saudade</td></tr>
<tr><td>Lagoa do Jacaré</td><td>Lagoa do Jacaré</td><td>Lagoa do Jacaré</td><td rowspan="3">Paraopeba</td><td>Lagoa do Jacaré</td><td>Lagoa do Jacaré</td></tr>
<tr><td>Serra de Santa Helena</td><td>Serra de Santa Helena</td><td>Serra de Santa Helena</td><td>Serra de Santa Helena</td><td>Serra de Santa Helena</td></tr>
<tr><td rowspan="3"></td><td>Sete Lagoas</td><td>Sete Lagoas</td><td>Sete Lagoas</td><td>Sete Lagoas</td><td rowspan="3">Sete Lagoas
(locally basal Samburá/ Carrancas conglomerates)</td></tr>
<tr><td rowspan="2">Carrancas</td><td>Paranoá</td><td rowspan="2">Vila Chapada</td><td>Paranoá</td><td rowspan="2">Jequitaí</td></tr>
<tr><td>Samburá</td><td>Carrancas Facies</td></tr>
</table>

Table 2.1. The Bambuí Group: evolution of the stratigraphy.

2.3 THE MIDDLE SÃO FRANCISCO REGION: SUBSIDENCE AND STRATIGRAPHIC CORRELATION

Stratigraphic correlation of Bambuí strata across the middle São Francisco region has been controversial for a long time.

Located on a stable portion of the craton (Alkmin et al. 1993), the area is unaffected by the bordering Brasiliano fold belts. However, from the analysis of satellite and radar images, faults are widespread and mostly normal faults (Rocio 2000 *unpublished*; Nobre-Lopes 2000 *unpublished*). The resulting structural pattern is quite different from the structures observed in the fold belts surrounding the craton (see Fig. 2.2). Important to say the area lacks studies concerning the tectonics, structural geology and sedimentology.

The main problem arises when comparing geologic sections outcropping on both sides of the São Francisco valley and neighbouring areas. The thickness of the sedimentary succession differs markedly and different formations outcrop regionally at the same topographic level suggesting fault control. For discussions regarding regional differences in the sedimentary pile thickness see Robertson (1963), Cassedanne (1972), (Dardenne 1979), and Lopes (1979).

Data suggesting differential subsidence of basement blocks comes from Lesquer et al (1981) that interpreted two paralleling and elongated gravimetric anomalies NNE-SSW as representing uplifted blocks of the basement related to active fractures of the basement. The western high zone is located in the Vazante region (Zn mineral deposits are present); the eastern uplifted block is situated in the middle São Francisco valley and probably related to a NNE-SSW fault along which the herein studied mineral deposits are located.

Another important fault system that affected the Bambuí sediments has a NNW-SSE trend and also resulted in differential subsidence of the basement blocks. This system is best observed in the field and on radar images on the left side of the São Francisco River valley; and was outlined by local mapping (Lopes 1979), magnetometric images (Rabelo and Santos 1979; Reis 2000 *unpublished*). Radar and satellite images also show clearly these faults (Rocio 2000 *unpublished*). Lopes (1979) and Dardenne (1979) also mentionned the importance of synsedimentary faults affecting the evolution of the Bambuí sedimentation.

Where differential tectonic subsidence is a dominant process, the sedimentary rocks outcrop regionally and are hundreds of meters thick; thickness changes due to the paleotopography of the basement are only tens of meters thick and defined by gradual thinning of the sedimentary record (this research).

Comparing the regional structural data with the overall sedimentary succession, two main sedimentary fault controlled domains are evident with different subsidence. These are located westward and eastward of the São Francisco River valley (Figures 2.3 and 2.4).

In the eastern domain the Bambuí Group is thicker than elsewhere indicating that greater subsidence occurred compared with neighouring areas. The stratigraphic section is ~700 meters thick (Brandalise et al 1980; Abreu-Lima 1997) and outcroping sediments belong to the upper formations of the Paraopeba Subgroup. The Sete Lagoas Formation is ~500 m thick and is buried under 250m of sediments related to the upper formations of the Paraopeba Subgroup.

In the western domain the lowermost outcrop is of the Sete Lagoas Formation (except small area of basement rocks) and is locally capped by pelitic sediments of the Serra de Santa Helena Formation. The sedimentary succession varies from 50 to 150 m (Januária region) to 350m at Itacarambi. Differences in thickness become important up to the north suggesting that neighbouring areas also subsided differently. In this domain differential subsidence of the blocks likely were related to the northwest/southeast fault system. Slump structures found in the lowermost outcropping units suggest synsedimentary faulting; there is no coarse material such as debris flows associated with disturbed layers that would be suggestive of a foreslope environment. In the eastern as well in the western domain, sediments at different stratigraphic levels were, and are unconformably overlain by Mesozoic sediments.

All of these data suggest that Sete Lagoas sedimentation occurred in a carbonate platform affected by grow-faults, and regional stratigraphic correlation of the Bambuí sedimentary succession is only possible if the differential subsidence and the influence of basement paleotopography are taken into account.

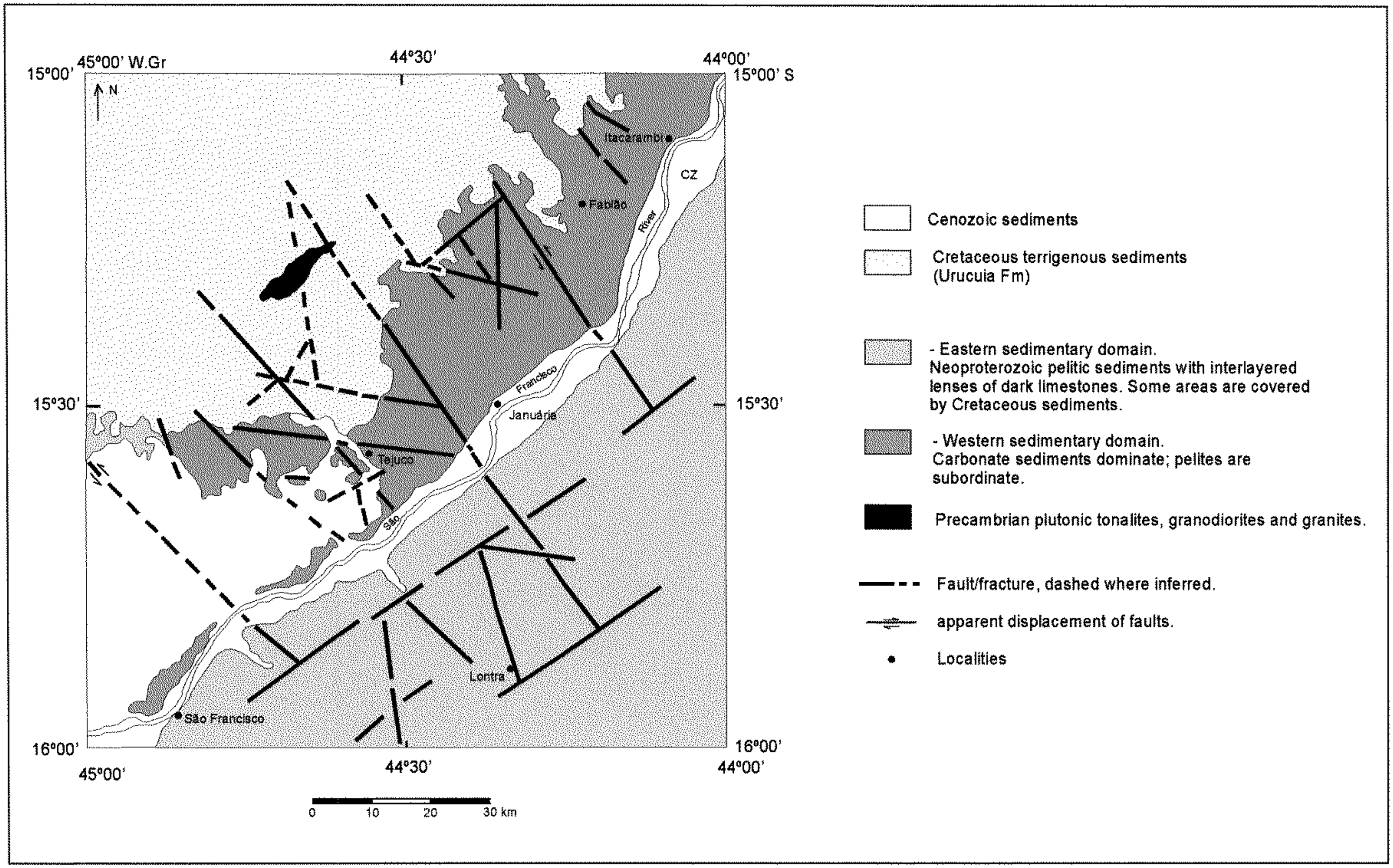


Figure 2.3. Simplified geological map of the Januária region and neighboring areas (Baptista and Meneguesso 1976; structural elements also from Rocio 2000 –*unpublished*).

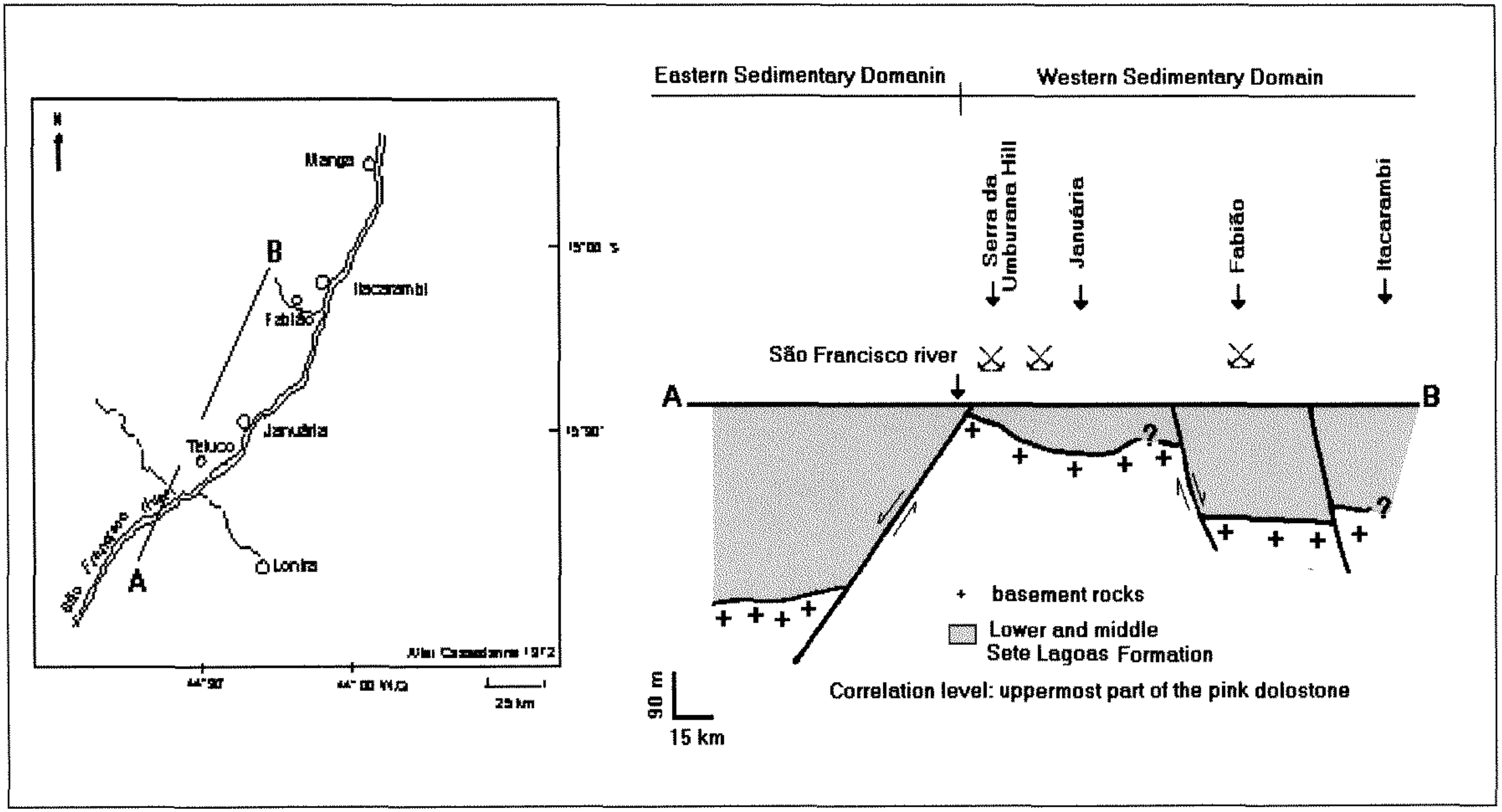


Figure 2.4. Schematic cross-section showing the main sedimentary domains in the middle São Francisco valley.

2.4 CONCLUSIONS

The Bambuí Group is a Neoproterozoic platform cover deposited over the São Francisco Craton. The craton is bordered by the Brasilia, Rio Preto, Riacho do Pontal, Sergipano and Araçuaí Belts of the Brasiliano Cycle (750-530 Ma) that also affect the Bambuí sediments along their limits. Far from the fold belts, on the cratonic areas the tectonic pattern is mainly normal faulting which caused vertical movement of blocks.

The Bambuí Group belongs to the São Francisco Supergroup comprising the following formations: Sete Lagoas, at the base (limestones and dolostones), Serra de Santa Helena (pelitic with lenses of limestones), Lagoa do Jacaré (limestones) and Serra da Saudade (pelitic with lenses of limestones), that altogether compose the Paraopeba Subgroup. Capping the subgroup, the Três Marias Formation with immature siliciclastic sediments ended the Bambuí sedimentation.

The sediments of the Bambuí Group were subaerially exposed and eroded during most of the Paleozoic and some of the Mesozoic. They are unconformably overlain during the Cretaceous by the terrigenous sediments of the Urucuia Formation.

The age of the Bambuí Group is constrained by $^{87}Sr/^{86}Sr$ data on limestones to be around 590 to 600 Ma.

In the middle São Francisco valley region the sedimentary pattern is closely related to tectonic subsidence and the main fault system trend NNE-SSW and NNW-SSE. Two main sedimentary domains, east and west of the São Francisco valley, were defined based on thickness variations of the sedimentary succession in conjunction with structural data. The thicker eastern sedimentary pile has more than 700m of Bambuí sediments having at its top the upper formations of the Paraopeba Subgroup. On the western side in the study area the upper formation, Serra de Santa Helena, is poorly exposed and outcrops only locally being eroded in most of the area. Important differences in the thickness of the sediments and the occurrence of synsedimentary faults suggest that blocks subsided differently.

In the Paleozoic and Mesozoic, erosion affected sediments of different stratigraphic levels of the group on western and eastern side of the São Francisco valley.

CHAPTER 3

JANUÁRIA MINERAL DEPOSITS

3.1 GENERAL SETTING

All along the middle São Francisco valley, scattered lead and/or zinc, silver rich small mineral deposits are hosted in brecciated dolostones; vanadium occurrences are also known (Figure 3.1). Fluorite is often present but the control seems not to be the same as that for the base metal deposits.

The brecciated dolostones are located in the Sete Lagoas Formation and characterize a specific and regionally widespread stratigraphic level.

Mineral deposits are characterized by specific assemblages of ore minerals composing distintive mineral districts, as the Januária zinc/silver district and the Itacarambi lead rich area.

All of mineralized areas have been related by most of the authors to a subaerial exposure event resulting in a meteoric karst development (see section 1.4 Previous Studies). The origin of the mineral deposits would be syngenetic or syndiagenetic to epigenetic with later remobilization (Beurlen 1973; Dardenne 1979; Lopes 1979; Rabelo 1981). Robertson (1963) is the exception; he considers the mineralizations as hydrothermal, MVT, and not related to an unconformity resulting from subaerial exposure.

Mineral deposits can be characterized as stratabound because though scattered regionaly, they are limited to a specific stratigraphic interval.

3.2 Zn/Ag JANUÁRIA MINERAL DISTRICT

Despite that sphalerite largelly dominates among the ore minerals, deposits were exploited only for their silver content. Only one small deposit was exploited for vanadium. Galena in general is very subordinate.

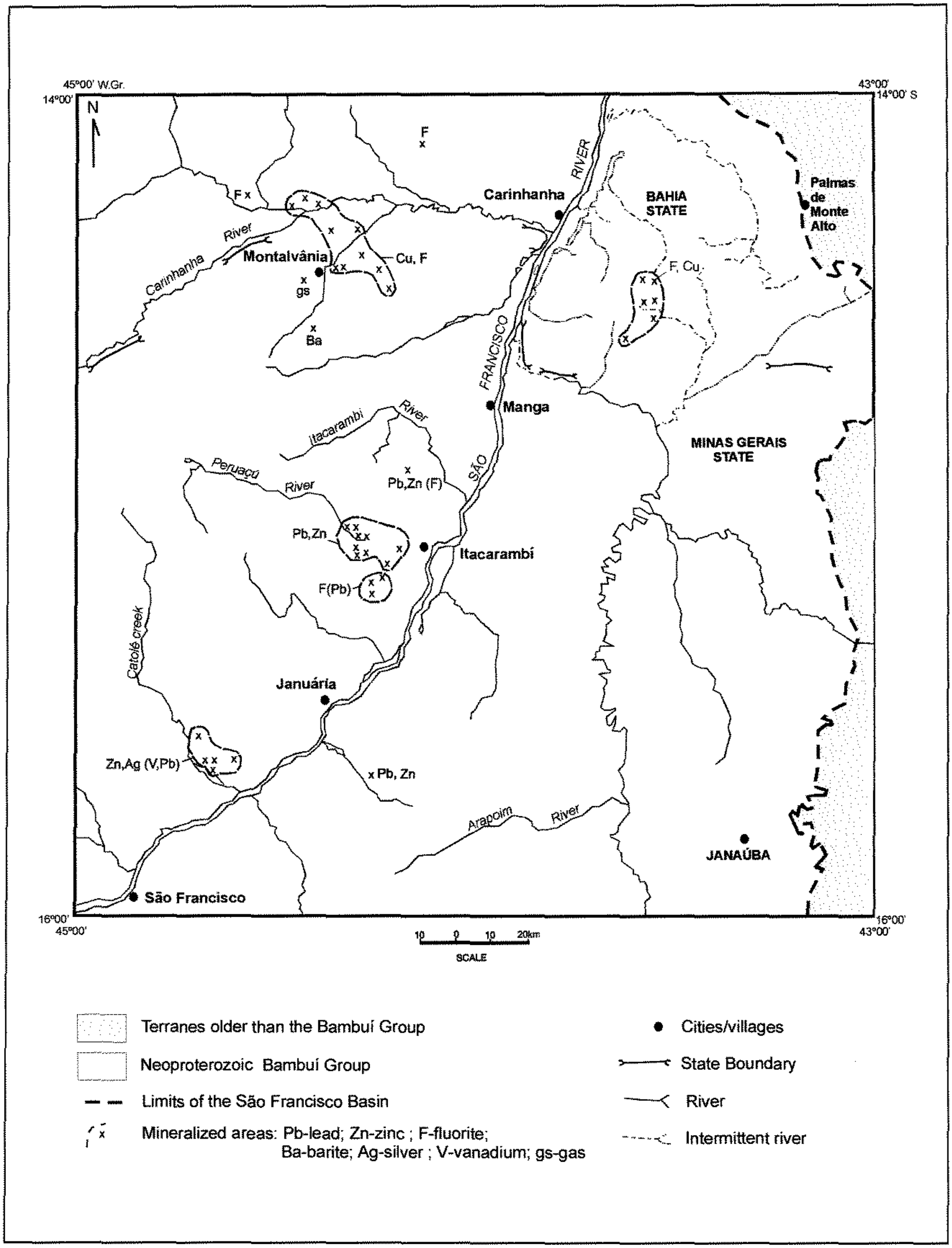


Figure 3.1. Main mineralized areas in the Bambuí Group along the middle São Francisco River.

Mineral deposits were small and data about tonnage are not precise. Cassedanne (1972) is the main source for data concerning ore mineralogy and exploitation of these deposits. Reference is made to a possible production of about 600 tons of silver in the region; the Zn content in the sphalerite would vary from 16 to 39% the latter retaining 17%ZnO; silver content of areas would vary from 0,9 to 18,6% whereas Pb varied from 0,15 to 2,64%. The ore minerals presented also appreciable amounts of Fe, Bi, and As. Exploitation of the deposits ended in the early sixties.

The main ore mineral was sphalerite in both honey and dark varieties. Little of it is still available for study; no core drilling was executed and in most mineralized outcrops ore minerals were almost entirely extracted.

The main mined areas are located near the Tejuco village, ~20 km southwest of Januária, and mineral deposits roughly concentrated in and around the Serra do Cantinho Hill, also named Serra da Prata Hill. Capão do Porco and Serra da Umburana Hills located tens of kms apart from the main area were also mined (see Figure 1.2).

Zinc/silver mineral deposits are hosted in dolostones consisting of extensive diagenetic replacement of limestones, and dolomite cements. Dolomite replacement hosting mineralization are mostly of coarse crystallinity but microcrystalline ones are also common (respectivelly ooid-intraclast dolostone member 6 and unit 7A of the dolomudstone member 7 of this research), and both types are strongly brecciated.

Microcrystalline dolomite mostly developed a brecciation pattern similar to crackle breccia (as shown in Ohle 1985), however local development of dissolution/collapse breccia occurs in some areas, as in the Serra da Umburana Hill. Coarse crystalline dolomite are strongly affected by dissolution/collapse breccia wich is more pronounced around mineralized areas.

The bulk of the mineral deposits are concentrated in the coarse crystalline dolomite and less commonly, in the lower part of the microcristalline ones.

Faults and fractures are uncommon in mineralized areas; faults are not easily recognized in the field also because of alluvial sediments of the São Francisco valley. However an extense fault zone of NNW-SSE direction is recognized in the southwestern part of the area, near Serra do Cantinho Hill (Baptista and Meneguesso 1976; Rabelo 1981; Rocio, 2000 *unpublished*). Topographic differences of correlated stratigraphic layers in the

Serra do Cantinho, Capão do Porco and Serra da Umburana Hills indicate incidence of normal faulting after deposition of the sediments.

The ore mineral, sphalerite, occurs filling vugs, cavities, small fractures and cementing dissolution/collapse breccias. Cassedanne (1972) describes important pockets of ore minerals: these and others features have disappeared because of intense exploitation.

3.3 ORE MINERAL AND GANGUE – GENERAL PARAGENESIS

Presently in outcrops one observes mainly honey and dark sphalerite, but willemite, vanadinite, fluorite and native sulfur can also be seen. Galena though described by Cassedanne (1972) was not observed during fieldwork. The main ore mineral was sphalerite though silver sulfide was also abundant.

Earthy iron oxides are locally observed, e.g. Maria Messias mine, cementing breccia fragments. Open fractures filled by hematite and having the walls lined by magnetite (Cassedanne 1972) were not observed in this research. Iron oxides stain pink all permeable dolomites near mineralized areas, especially the coarse-crystalline ones; in the microcrystalline dolomite staining is reduced to a few cms to dms because of the very low permeability. Iron oxides are mainly hematite but limonite can also be present; iron oxides also occur inside late, high amplitude stylolites.

Cassedanne (1972) suggests that the dark variety of sphalerite crystallized prior than the honey ones. Petrographically dark sphalerite lines pore-space having clear sphalerite in the middle; this relationship seems to confirm that honey sphalerite is later than the dark one.

Willemite as needles occurs in or fills cavities and vugs in the brecciated dolostone; late calcite, fluorite and/or bitumen occlude the remaining open spaces.

Under SEM sphalerite exhibits patchy and complexe textures because of multiples solid inclusions; it shows high content of silver as well as lead, arsenium, copper, cadmium, vanadium (Figure 3.2).

The main and widespread solid inclusions are of AgS, some of them having solid inclusion of zinc sillicate (willemite); native silver is subordinate.

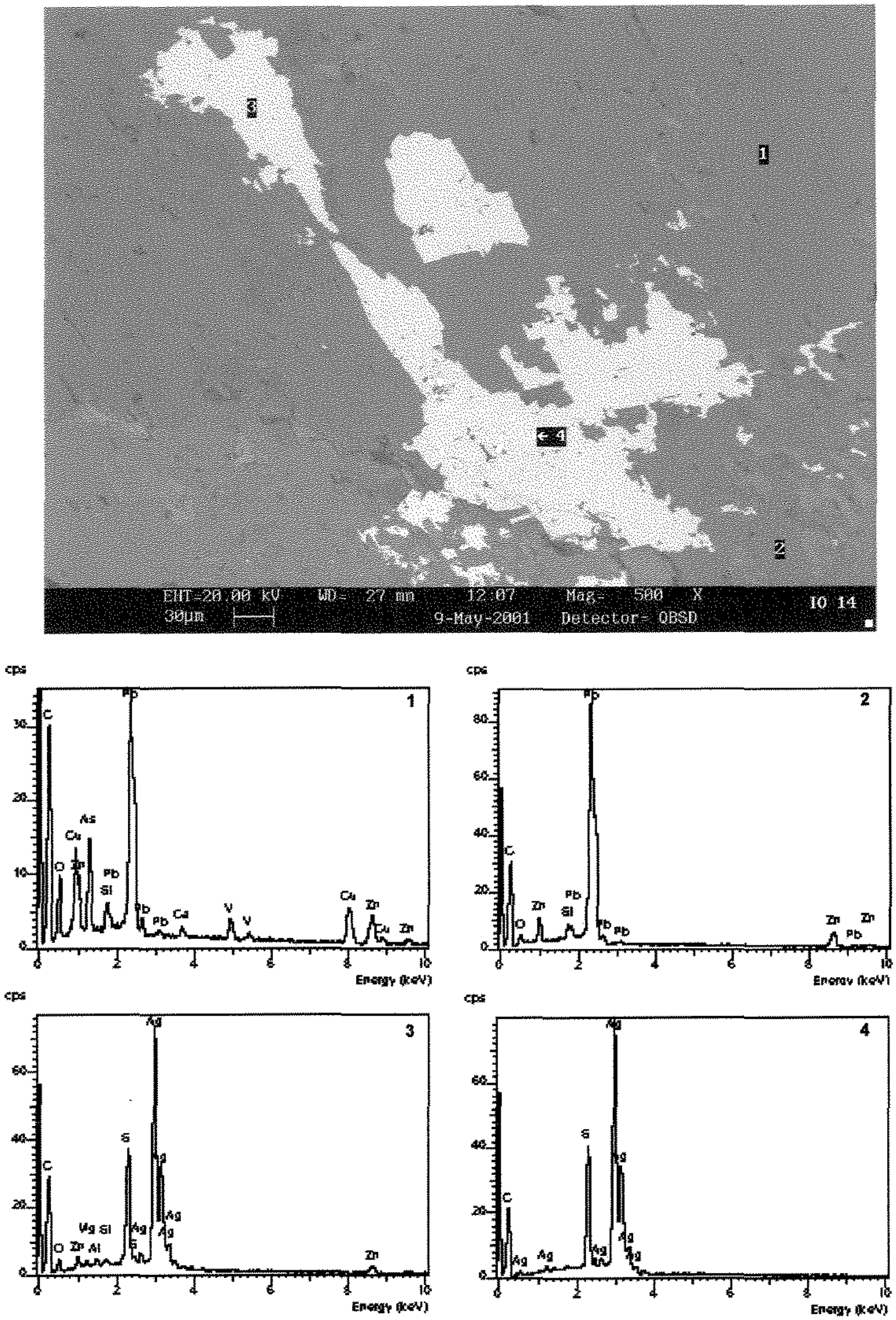


Figure 3.2. Solid inclusions in honey sphalerite under SEM

Arsenic sulfides are complex and include V and Cd; Pb occurs as solid inclusions in the form of either galena or native lead.

The zinc silicate where occurring as needles filling cavities in the dolostone show very low content of Ag and Pb.

Vanadium occurs as small pockets in the coarse replacement dolostone but not in direct association with the sphalerite.

The main gangue mineral is dolomite but calcite is also widespread; fluorite and quartz are subordinate. Characteristically dolomite cements around mineralized areas are zinc rich and iron poor. The exception is the white saddle dolomite which display iron oxides solid inclusions.

Quartz and fluorite are late than the sulfide mineralization. The position of the elemental sulphur in the paragenetic sequence is difficult to stablish because not found in association with the ore minerals.

Replacement dolomites	--------------
Dolomite cement I (mostly saddle form)	------
Dark sphalerite	-----------------
Honey sphalerite	---------------
Willemite	------ ------
Iron oxide	----------
Dolomite cement II (white saddle forms)	--------
Late calcite	------
Fluorite	--
Bitumen	---- ---- ---- ----

Table 3.1. Generalized parasequence for ore and gangue minerals of the Januária district. For more details see Chapters 5, 6 and 7.

Thus, the sequence of mineral deposition at the Januária district is very simple (depending of the material collected from old mined areas). It was determined from studies of ore and gangue minerals. The most important criterion used for establishing the position of a mineral in the parasequence was its three-dimensional position relative to others mineral as observed in the field, hand samples and polished/thin sections.

3.4 CONCLUSIONS

The Januaria district is one of the mineral districts in the middle São Francisco region; it encompasses several zinc/silver mineral deposits of low tonnage, most of which related to a brecciated/collapsed dolostone level. The brecciated dolostone level is regionally widespread and rhoughly compose a regional stratigraphic marker.

Dolostones result from extensive diagenetic replacement of limestones and dolomite cementation. Most of the Zn/Ag mineral deposits are hosted in brecciated coarse dolostones, but some of them are also hosted in microcrystalline ones. Mineral deposits are stratabound and ore mineral occur cementing dissolution/collapse breccias or as open-space filling of cavities and fractures.

The main ore mineral is sphalerite (honey and dark varieties), the deposits however were exploited just for their silver content. Under SEM it is defined that sphalerite has a high content of silver and others heavy metals. Galena is very subordinated being observed only as solid inclusions in sphalerite. Paragenetically sphalerite postdates replacement dolomite, the main events of dissolution/brecciation and rhomboedral saddle dolomite. Honey sphalerite is later than the dark one and both of them are prior to iron oxides affecting white saddle dolomite as solid inclusions.

Late calcite is prior to and affected by fluorite, bitumen and late fracturing.

CHAPTER 4

THE BAMBUÍ GROUP IN THE JANUÁRIA REGION

4.1 INTRODUCTION

Sediments of to the Bambuí Group, in the middle São Francisco river valley, were deposited on a carbonate platform affected by growth faults and exhibiting large fault-blocks that subsided differently (see Chapter 2). The Januária region is located in a more stable, less subsiding area as compared with neighbouring portions of the basin.

The carbonate sediments belonging to the Sete Lagoas Formation are covered by fine terrigenous sediments of the Serra de Santa Helena Formation, both constituing the lowermost part of the Paraopeba Subgroup. Sediments of the Bambuí Group during the Paleozoic and part of the Mesozoic were eroded and unconformably covered by Cretaceous terrigenous sediments.

This study will deal only with sediments of the Sete Lagoas Formation, the carbonate unit hosting the mineral deposits of the region. Outcrops of pelitic sediments are scarce and poorly developed in the Januária region.

Our stratigraphic assignements are similar to those of previous workers (Robertson 1963; Dardenne 1979; Lopes 1979 and Abreu-Lima 1997) although this research is the first one to attempt a detailed sedimentological study aiming at defining sedimentary cycles and the paleogeography of the area.

4.2 LITHOSTRATIGRAPHY OF THE SETE LAGOAS FORMATION

The lithostratigraphy of the Sete Lagoas Formation was defined by field inspection, with description and measurement of stratigraphic sections, petrographic studies and isotopic analyses.

The stratigraphic section of Grão Mogol Hill is here defined as the type-section of the Januária region allowing stratigraphic correlation with mineralized areas. Location of the described sections can be seen in the Figure 1.2.

In this research the Sete Lagoas Formation is informally divided into 7 members easily recognized in the field; the uppermost member is divided into 2 units. Lateral and vertical variations of the members are evident across the whole area and especially related to the their thickness, differences of units in a member, stromatoid morphologies and size of bioherms; locally some members are missing or very subordinate. The main variations are observed in the southwestern part of the study area encompassing the Capão do Porco and Serra da Umburana Hills.

Besides Grão Mogol Hill, lower members were described at the Progeo quarry, the Bom Jantar and Itapiraçaba hills; the middle members and the basal unit of the upper member were described at the Serra do Cantinho, Serrotinho and Serra da Umburana Hills. The lower and middle members were also described at Capão do Porco Hill. The upper members are inacessible or have been eroded in most of the hills of the region.

Some units do not outcrop in the study area as the basal thin layer of pink dolomudstones which lies over granitic and dioritic rocks belonging to the crystalline basement (Dardenne 1979; Abreu-Lima 1997); this level is stratigraphically below the herein described basal member.

Figure 4.1 show the stratigraphic correlation between members of the Sete Lagoas Formation in the Januária region whereas Table 4.1 summarizes characteristic features of the members.

Figure 4.2 in turn shows the stratigraphic section of Gão Mogol Hill that will be used as reference in the text.

4.2.1 MEMBER 1 – ARGILLACEOUS LIME MUDSTONE

It is the basal member with thicknes ranging from 5 to 20 meters; the base is not exposed. Thinning-up cycles 2 to 3m thick are observable at Bom Jantar hill but cannot be clearly defined elsewhere.

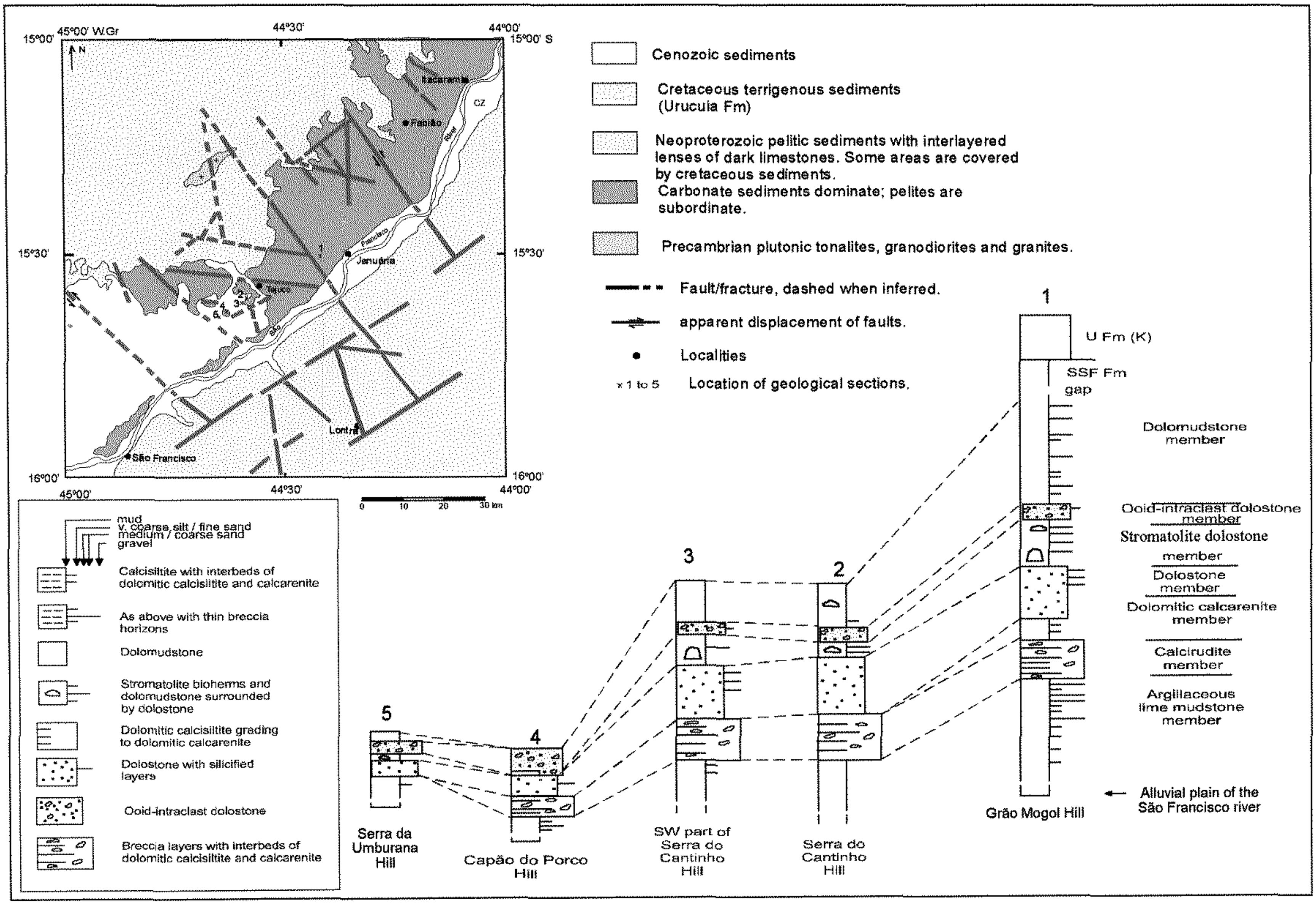


Figure 4.1. Stratigraphic correlation between members of the Sete Lagoas Formation – Januária region.

Member	Lithology	Color	Grain size	Basal contact	Sedimentary structures	Special features	Sedimentary cycle
1 - Argillaceous lime mudstone	calcisiltite, dolomitic calsisiltite, very-fine calcarenite (intrapeloidal packst to grstn), lime mudstone	dark gray	silt;very fine to fine sand	do not outcrops	planar-parallel bedding, low-angle cross-lamination	thin lamination, microstylotes, normal grading, nodular bedding	Basal sh-up. succession (regressive)
2 - Calcirudite	calcirudite (mainly rudstones), dolomitic calcisiltite, dolomitic calcarenite	medium gray	pebbles; interbeds vary from silt to fine sand	gradational	normal grading, HCS, planar-bedding, fine-scale lamination	massive, ungraded rudstones; slump structure; nodular bedding	Basal sh-up. succession (regressive)
3 - Dolomitic calcarenite	dolomitic calcarenite (mostly intraooidal packst to grstn), dolomitic calcilsitite, lime mudstone, dolostone	medium gray	silt; medium sand	sharp	parallel lamination, low-angle cross-lamination, HCS and SCS	microstylotites	Intermediate sh-up. succession (transgressive)
4 - Dolostone	dolostone with or without ghosts of allochems, silicified dolostone, silicified dolarenite; rare dolorudite	light gray	medium sand; coarse to very-corse sand (silicified dolarenite); granule to pebble	undefined;clear change in the sedimentary pattern	planar cross-bedding, rippled bedding	dissolution/ collapse breccia	Intermediate sh-up. succession (transgressive-highstand)
5 - Stromatolite dolostone	stromatolite dolostone, dolosilstite	pale gray	silt	sharp	fine-scale lamination	dissolution on top of the basal bioherms	Intermediate sh-up. succession (highstand)
6 - Ooid-intraclast dolostone	ooidal dolostone, ooid-intraclast dolostone and intraclast-pseudo intraclast dolostone (grstn to packst); intraclast dolostone (packst to wackst)	light gray to pink	fine to very-coarse sand	gradational and sharp (with stromatolites)	remains of planar, bidirectional and trough cross-bedding	dissolution/collapse breccia	Intermediate sh-up. succession (regressive)
7-Dolomudstone (comprises the units 7A, basal, and 7B)	dolomudstones with lenses of ooid, intraclasts and/or peloids; tufa-like (Unit 7A); dolomudstones with lenses of intraclasts, peloids and microphytolites; stromatolite dolostone (Unit 7B)	pale and dark gray	silt and very-fine to fine sand (units 7A and 7B). Interbeds are of medium to coarse sand; basal lags are mostly granule to pebble.	sharp and gradational	fine-scale lamination, planar-parallel bedding low-angle cross-lamination	meniscus and pendant cements, tepees, desiccation cracks	Intermediate sh-up. succession (Unit 7A); regressive, subaerial exposure. Upper sh-up.succession: small transgressive-regressive successions (Unit 7B)

Table 4.1. Main features of described members: Sete Lagoas Formation - Januária region

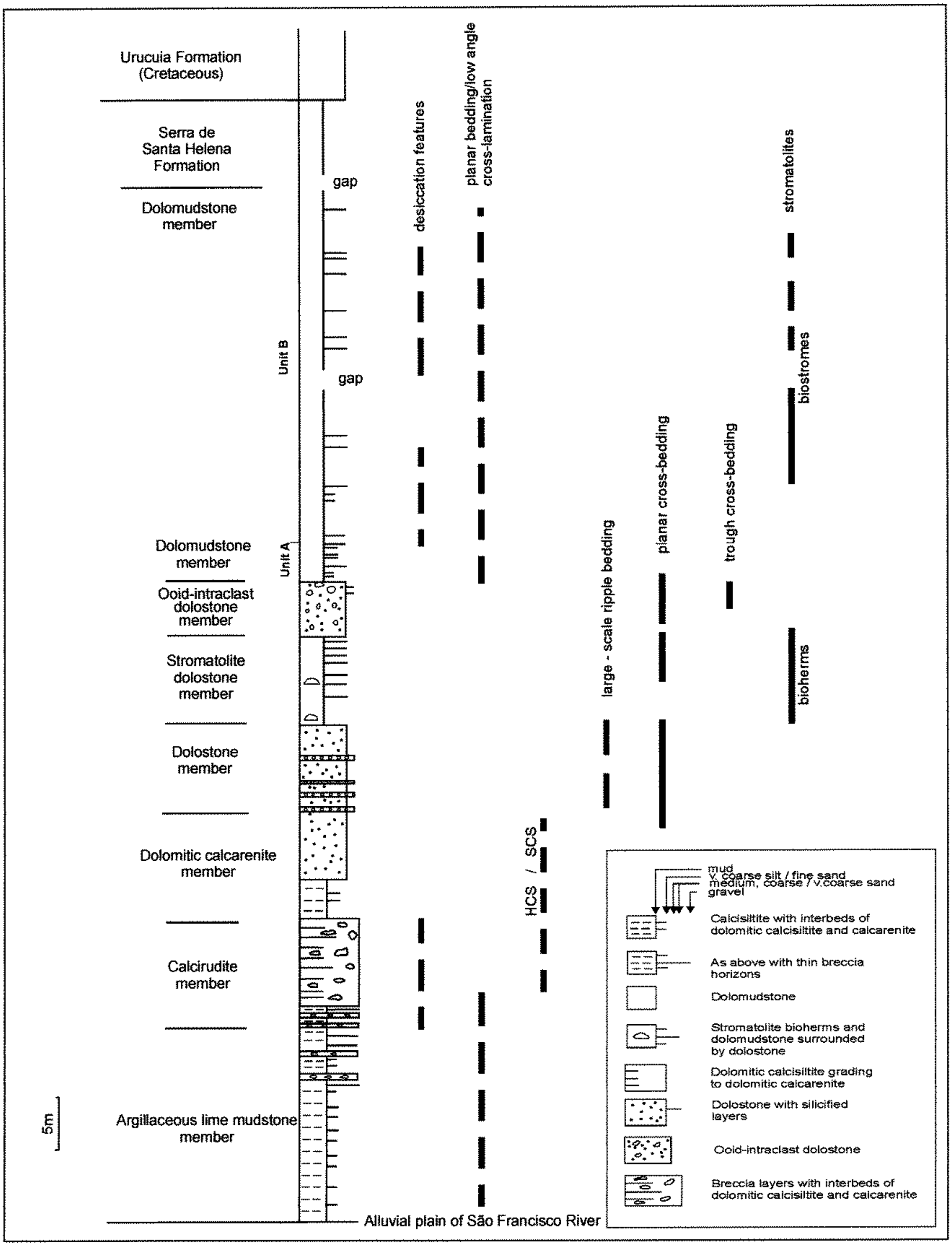


Figure 4.2. Lithostratigraphy and main sedimentary features in the Grão Mogol Hill - Januária region.

Argillaceous lime mudstones are medium to dark-gray, display planar-parallel bedding and represent the background sedimentation; layers are cm to mm thick and capped by a thin argillaceous film. Compaction features are widespread.

Interbeds are common and laterally persistent at outcrop scale; most of them are cm thick and made up of finely laminated limestones, some of them displaying low-angle cross-lamination, and breccias. The contact between muddy limestone and interbedded strata is always sharp (Fig. 4.3a).

Units displaying low-angle cross-lamination are silt size or very fine sand; normal grading is common. Locally, on the upper part of the member, cross-bedded units can be dm thick, laterally persistent at outcrop scale and second-order truncations can be present. These structures are similar to hummocky cross-stratification (HCS).

Breccia and microbreccia are locally observed in the uppermost part of the member; texturally they are ungraded rudites with poorly sorted sand-sized matrix and floatstones.

Thinly laminated lime mudstones were observed locally in the uppermost part of the member, are about meter thick and laterally limited to a few meters (Fig. 4.3b).

Physical and/or chemical compaction exerts strong influence in the macroscopic and microscopic aspect of the lime mudstones; these processes are responsible for the development of nodular/fitted limestone, which are particularly common in the lowermost part of the member.

Chemical compaction or pressure-solution features are mostly represented by microstylolites with subordinate non-sutured seams (Fig. 4.3 c, d). Stylolites of greater amplitude contain residual dark material and cut microstylolites.

Lime mudstones as petrographically defined encompass calcisiltite, dolomitic calcisiltite and very fine sand-sized intrapeloidal wackestones to grainstones.

Dolomitic calcisiltites are often laminated but may also display massive, crudely laminated or nodular fabrics; interbeds of poorly laminated intrapeloidal wackestones to packstones show numerous nodules of chert (Fig. 4.3.c). Areas with clear dolomite crystals are common.

Figure 4.3a-4.3d. Member 1 –Argillaceous lime mudstone

a) Basal outcrop of the argillaceous lime mudstone member; plane-parallel bedding dominate with interbeds of nodular and low-angle cross-lamination are also common. Location: Argillaceous lime mudstone member, Progeo Quarry.

b) Thinly laminated lime mudstones in outcrop. Location: Argillaceous lime mudstone member, Gão Mogol Hill.

c) Thin section photomicrograph of intrapeloidal wackestone to packstone showing dissolution seams, early stylolite and small round nodules of chert. Plane light. Location: Argillaceous lime mudstone member, Progeo Quarry.

d) Thin section photomicrograph of thinly laminated calcisiltite displaying numerous early microstylolites. Plane light. Location: Argillaceous lime mudstone member, Bom Jantar Hill.

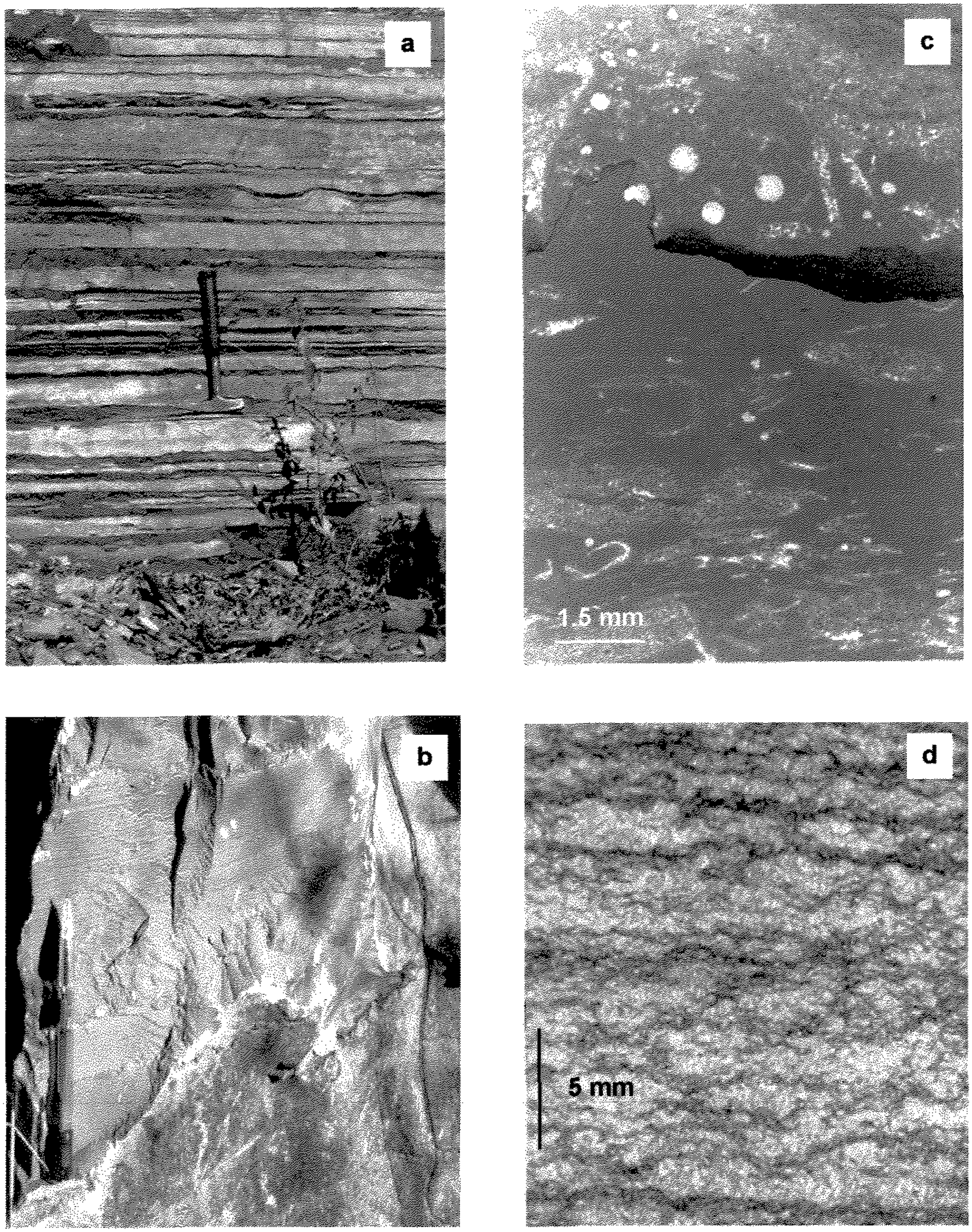


Figure 4.3. Member 1 – Argillaceous lime mudstone.

The thinly laminated calcisiltites have the appearance of rhythmites, and are made up of alternation of light and dark laminae (couplets). Light laminae are basal, mm thick and made up of coarse silt size peloids; they do not display compaction features. The dark laminae are submm to mm thick, muddier than the clear ones and overprinted by microstylolites. Where strongly affected by compaction the banding becomes irregular (Fig. 4.3d). Black peloids (fine sand), not well preserved, are concentrated or scattered in the dark layers. There is no dolomite associated with this microfacies.

Layers displaying low-angle cross-lamination are made up of peloidal calcisiltite, and intrapeloidal packstone to grainstone (very fine sand). Microstylolite, mostly bedding-parallel, is the main compaction feature. Dolomite crystals are very subordinate.

Micritic layers of grumelous texture is subordinate, and made up of peloidal to clotted micrite; display large areas filled with sparry calcite. They lack compaction features except for late stylolites.

Breccias and microbreccias are made up of lamelar intraclasts derived from early-lithified neighbouring sediments; massive calcisiltite, intrapeloidal wackestone and limestone with grumelous texture are the main components.

4.2.2 MEMBER 2 – CALCIRUDITE

The calcirudite member is a distinctive marker unit frequently recognized in the lowermost part of Sete Lagoas Formation. Calcirudites are mostly flat pebble breccias with interbeds of calcarenites displaying low-angle cross-lamination similar to hummocky cross-stratification (HCS), microbreccias, and lime mudstones. Intraclasts are traceable to the subjacent layers.

Breccia layers are commonly lensoidal and highly variable over short distances in terms of the thickness of the beds (dm to m), the size and distribution of intraclasts, the fabric and sedimentary structures. Intraclast sheet-like brecccias are less common.

The basal contact is sharp; the upper contact can be sharp with lime mudstones and layers displaying HCS, or gradational to lime mudstones (Fig. 4.4a, b).

Figure 4.4a – 4.4d. Member 2 - Calcirudite

a) Poorly sorted rudstone made up of lamelar intraclasts displaying crude normal grading; bed tops grades to lime mudstones with gentle slopes on the top. Basal contact is sharp-based with lime mudstones. Location: Calcirudite member , Bom Jantar Hill.

b) Ungraded rudstone made up of well-rounded intraclasts having in situ boken layers of lime mudstone. Location: Calcirudite member , Bom Jantar Hill.

c) Breccia layer with intraclasts arranged as small tepee-like structure. Location: Calcirudite member, Grão Mogol Hill.

d) Strata displaying low-angle cross-bedding similar to hummocky cross-stratification (HCS). Note second order truncation on the upper part of the outcrop. Location: Calcirudite member, Itapiraçaba Hill.

Texturally calcirudites are mostly poorly sorted rudstones (Fig. 4.4a and b); floatstones are scarce.

Rudstones are ungraded to crudely graded; normal grading and grading by diminution of clasts is secondary as is inverse grading. Bed tops grading to lime mudstones may display a gentle slump structure on the top (Fig. 4.4a). Few layers are conglomerates made up of well-rounded intraclasts (Fig. 4.4b). Microbreccia layers can be clast or matrix-supported; intraclasts are mostly lamelar and size varies from mm to cm.

Petrographically, intraclasts consist mostly of dolomitic calcisiltites and dolomitized intrapelmicrite. The matrix is poorly sorted, ranging from sand to granule in size, and compositionally similar to the intraclasts.

Some layers seem to be rudstones but lamelar intraclasts are angular and have been only slightly rotated from their original positions in the bedding plane.

Intraclast arrangement suggesting tepee structure is also present (Fig. 4.4c); mud cracks are scarce.

Cross-bedded units similar to HCS (Fig. 4.4d) are dm thick, frequently exhibit second-order truncations (hummocky zone of Dott and Bourgeois 1982) and are made up of laminated dolomitic calcisiltites displaying normal grading or fine dolomitic intrapeloidal packstones to grainstones.

Very thinly laminated lime mudstones similar to rhythmites as already described in the member 1 occur sporadically, in different stratigraphic positions, associated with breccia layers.

Interlayers of lime mudstones are cm thick and consist of dolomitic calcisiltite displaying planar-parallel bedding. Their mud content is low and compaction features are scarce.

Although rare, nodular lime mudstones squeezed between breccia and cross-bedded layers can be observed. Compaction over muddy sediments is also responsible for the development of pseudobreccia layers.

Dolomitization is partial, replacive, and texturally destructive, planar-s to e, and of very fine crystallinity. Replacement dolomite occurs as scattered rhombs over intraclasts (10 to 20%); over the matrix, replacement dolomites compose a loosy mosaic (~50%).

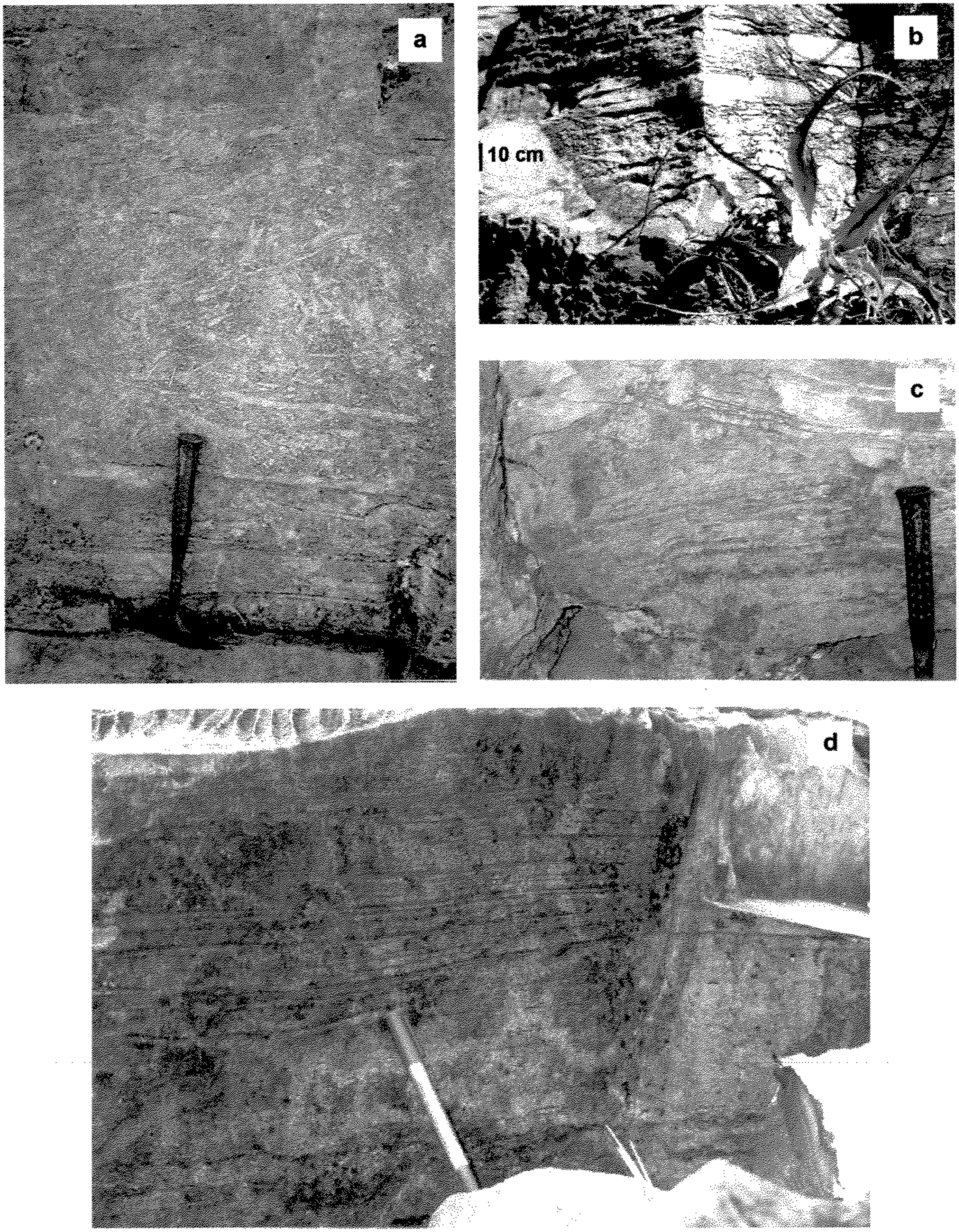


Figure 4.4. Member 2 – Calcirudite.

4.2.3 MEMBER 3 – DOLOMITIC CALCARENITE

The dolomitic calcarenite member is regionally widespread and ~10m thick at Grão Mogol Hill. Carbonate sediments are medium to light gray and exhibit coarsening and thickening upwards.

In the lowermost portion of the member the common sedimentary pattern is defined by dm thick lime mudstones layers displaying relatively flat lamination with interbeds of low-angle cross-lamination.

In cross-bedded units, laminae overstepping one another laterally at a very low angle (Fig. 4.5a) are similar to hummocky cross-stratification (HCS). The lower bounding erosional surfaces are almost flat and bedding-parallel; bed sets are cm to dm thick, tabular and laterally persistent at the outcrop scale.

Microbreccia layers are mm to dm thick, disorganized or display normal grading; are common in the southwestern part of the study area.

Upwards lime mudstones and microbreccia become more and more subordinate and grainy sediments with frequent HCS dominate. This lowermost portion is around 7m thick.

In the uppermost part of the member interbeds of lime mudstone are absent and cross-bedded grainstones (Fig. 4.5b) with prominent reactivation surfaces showing concave upwards orientation dominate; reactivation surfaces of convex orientation is also observed.

The resulting pattern is similar to the amalgamated hummocky stratification of Dott and Bourgeois (1982). It is difficult to virtually impossible to distinguish first-order from second-order truncations. Cross-stratification similar to swales (SCS) are subordinate and always in association with HCS. "Hummocks" and "swales" are mainly asymmetrical in cross section. The idealized Hummocky Stratification Sequence described by Dott and Bourgeois (op. cit.) was never fully observed in the study area. It is important to note that the massive uppermost sandier unit is made up of allochems coarser than fine to very fine sand, characteristic of HCS (Dott and Bourgeois 1982).

In the southwestern part of the area the thickness of the member decreases and lacks lime mudstone. The main sedimentary structure is planar cross-bedding; reactivation surfaces are common.

Petrographically fine sediments are represented by dolomitic calcisiltite that frequently display normal grading, and dolostones of peloidal to grumelous textures.

Thin micritic, undulating and roughly parallel films possibly of microbial origin are the main source of intraclasts making up the microbreccia layers.

Compaction features are scarce, mainly bedding parallel microstylolites.

Dolomitization strongly affects grainy sediments; the most common allochems are intraclasts and ghosts of possible ooids. Remains and ghosts suggesting former ooids are designated as pseudo-ooids.

Relative proportion of allochems varies greatly but intraclasts seem dominant over pseudo-ooids in the lowermost part of the member (Fig. 4.5c). Pseudo-ooids appear to be dominant in the middle and uppermost intervals (Fig. 4.5d), though intraclasts are still present.

Dolomitic calcarenites are intrawackestones to packstones and intrapseudo-ooidal to pseudo-ooidal packstones to grainstones; allochems seems to be of medium to coarse sand.

Dolostones with or without remains of allochems are common in the uppermost part of the member.

Dolomitization is replacive, texturally destructive, planar-s to e, a medium crystalline mosaic of dolomite with scattered coarse crystal rhombs.

4.2.4 MEMBER 4 - DOLOSTONE

The dolostone member is regionally widespread with thickness ranging from 2 to 7m. The basal contact with the dolomitic calcarenite member is marked by an abrupt change in the character of sedimentation, from rippled-bedding with numerous reactivation surfaces (dolomitic calcarenite member 3) to planar cross-bedding with current ripple interbeds (dolostone member 4).

Dolostones characteristically exhibit low-angle planar cross-bedding with tangential foresets (sets are dms thick) with interbeds of silicified current-ripple bedding of strongly tangential to sigmoidal foresets.

Figure 4.5a – 4.5d. Member 3 – Dolomitic calcarenite

a) Outcrop of the lowermost part of the Dolomitic calcarenite member showing relatively flat laminations with thin interbeds of low-angle cross-lamination (hummocky units). Location: Dolomitic calcarenite member, Grão Mogol Hill.

b) Outcrop of the uppermost part of the Dolomitic calcarenite member with dominance of amalgamated hummocky units with truncated surfaces. Some swaley cross-stratification can be seen on the left side of the photo. Location: Dolomitic calcarenite member, Grão Mogol Hill.

c) Thin section photomicrograph of dolomitic calcarenite made up of well-rounded intraclasts, most of them lamelar. Replacement dolomitization is partial but texturally destructive and strongly affects the intraclasts. Plane light with a white card (Folk's technique). Location: lowermost to middle part of the Dolomitic calcarenite member, Grão Mogol Hill.

d) Thin section photomicrograph of dolomitic calcarenite made up of well-rounded allochems; intraclasts are mostly ovoids and lamelar ones subordinate. Partial dolomite replacement; dolomitization is texturally destructive. Plane light. Location: middle to uppermost part of the Dolomitic calcarenite member, Grão Mogol Hill.

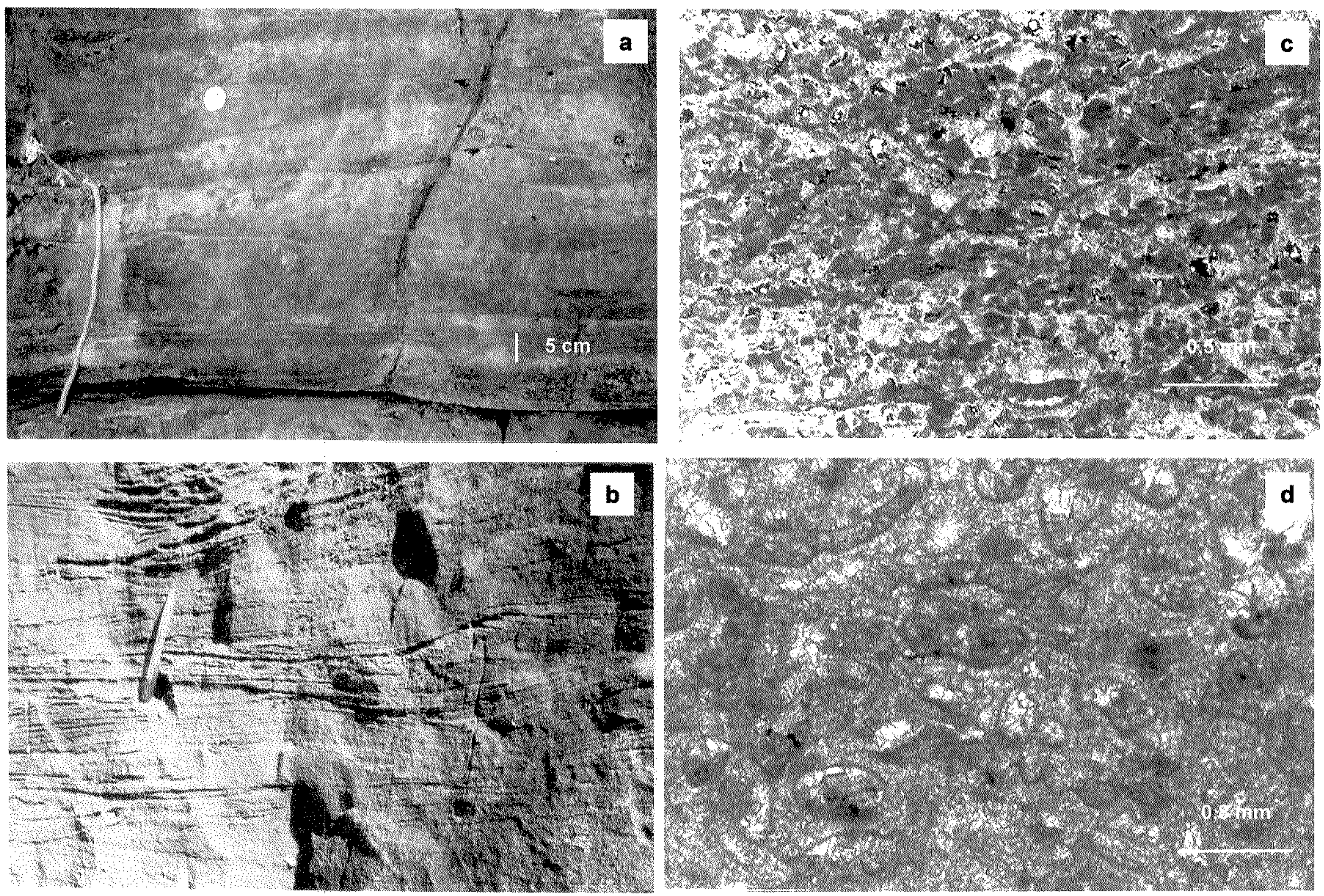


Fig. 4.5. Member 3 – Dolomitic calcarenite.

Planar cross bedding is of medium scale and current-ripples of medium to large scale (Fig. 4.6a, b). Dolorudites with normal grading are subordinate and made up of subrounded lamelar intraclasts. Units displaying HCS/SCS, commonly observed in the uppermost part of the member stratigraphically below, are no longer observed.

In the southwestern area silicified rippled-bedding are less common and of medium scale.

Allochems, wherever observable, are micritic remains (peloids?), pseudo-ooids and well rounded silicified grains (Fig. 4.7a, b, c, respectively) without internal texture preservation.

The dolomitization of the sediments makes the description of the petrographic types difficult, because it erased most of the characteristics of the original sediment, including internal texture of allochems or even the allochem itself.

Despite this, it was possible to define dolostones, silicified dolostones, pseudo-ooidal dolostones, dolostones with remains of micritic grains and silicified dolarenite.

Dolostones are massive, resulting from fabric destructive replacement and their textures are discussed in the Chapter 6.

Silicified dolostones are made up of a mosaic of planar euhedral to subhedral, medium to coarse dolomite crystals; no ghosts of allochems are observed. Megaquartz and chert replacement affect almost 40% of the dolostone (Fig. 4.7d).

Pseudo-ooidal dolostone exhibits few ghosts of well-rounded grains apparently of medium size or coarser (Fig. 4.7b).

Dolostones with micritic remains apparently are of medium size or eventually coarser; in a general way, micritic allochems seem finer than pseudo-ooidal ones.

Silicified dolarenites are poorly sorted, medium to very coarse grainstones; some allochems are coarser than sand. Allochems are well rounded, lamellar to ovoid or irregular; some of them are composite intraclasts made up of well-rounded medium to coarse grains (Fig. 4.7c). Lack compaction features.

Locally dolostones are affected by dissolution/collapse brecciation.

Figure 4.6a – 4.6b. Member 4 – Dolostone

a) Outcrop of dolostone displaying planar cross-bedding cut by rippled and better preserved silicified grainy layers. Location: Dolostone member, Grão Mogol Hill. (scale = 5cm high)

b) Detail of outcrop of dolostone showing planar cross-bedding dm thick and rippled silicified grainy layers. Although replacement dolomitization was texturally destructive, sedimentary structures are still observable. Location: Dolostone member, Grão Mogol Hill. (scale = 4cm long)

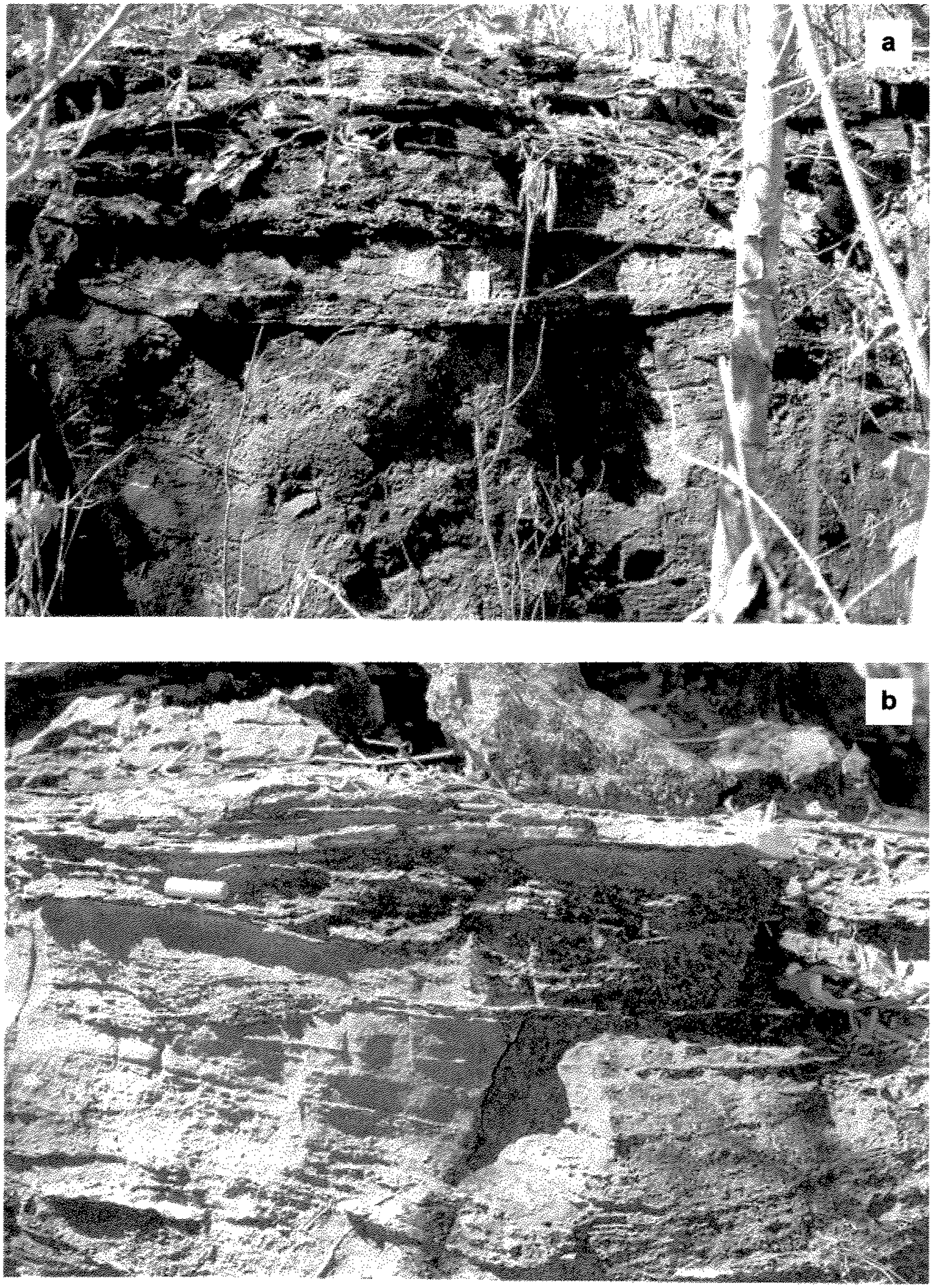


Figure 4.6. Member 4 – Dolostone.

Figure 4.7a – 4.7d. Member 4 – Dolostone member: main petrographic textures

a) Thin section photomicrograph of dolostone with poorly preserved micritic remains. Replacement dolomitization is fabric destructive and erased most of the characteristic of the allochems or the allochem itself. Plane light. Location: Dolostone member, Grão Mogol Hill.

b) Thin section photomicrograph of dolostone where remain of well-rounded allochem is still visible in a matrix of replacement dolomite. Plane light. Location: Dolostone member, Grão Mogol Hill.

c) Thin section photomicrograph of poorly sorted silicified dolarenite (grainstone). Plane light. Location: Dolostone member, Grão Mogol Hill.

d) Thin section photomicrograph of silicified dolostone; there is no remains of allochems. Plane light. Location: Dolostone member, Grão Mogol Hill.

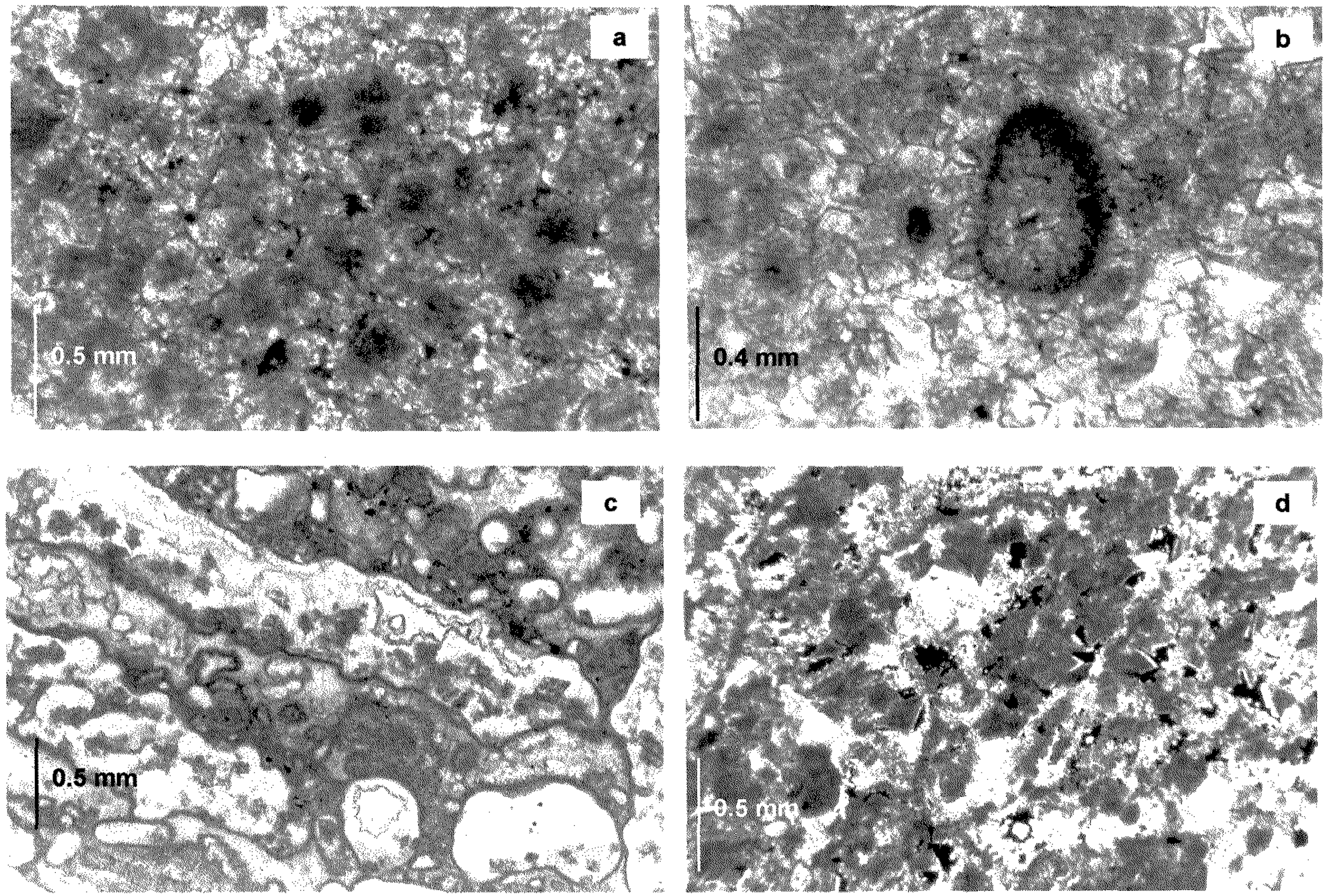


Figure 4.7. Member 4 – Dolostone: main petrographic textures.

4.2.5 MEMBER 5 – STROMATOLITE DOLOSTONE

The stromatolite dolostone member is composed of stromatolitic and non-stromatolitic dolostones. The member are of regional importance and better exposed at Grão Mogol and SW part of the Serra do Cantinho Hills; can be missing or poorly developed in the southwestern area.

Stromatolite dolostones comprise bioherms of different sizes, built by stromatoids of distinctive morphologies. Non-stromatolite dolostones are mostly finely laminated carbonate mud that settled down in more protected areas.

The basal stromatolite buildups developed on ooidal sediments or intraclastic beds belonging to the lowermost part of the dolostone member 4; the uppermost and smallest bioherms can be hosted in carbonate rocks of the ooid-intraclast dolostone member 6.

Stromatolite dolostones

The basal stromatolitic bioherms are always the higher ones and form continuous to close-spaced buildups 3 to 7 m high with sharp walls. They are laterally limited but may be exposed for almost 100m, as at Serra do Cantinho Hill.

The stromatolitic bioherms are made up of stromatoids of varying morphologies and size (Fig. 4.8). Stromatoid morphologies are randomly distributed, the commonest ones being contiguous to closely spaced pseudo-columnar to columnar/bulbous stromatoids cm to dm high (Fig. 4.8a). Branched stromatoides are scarce (Fig. 4.8b). Dolomudstones and "fine peloidal packstone" fill the intercolumnar spaces. Toward the top bioherms become smaller, openly spaced, and stromatoids are mostly nodular to bulbous (Fig. 4.8c).

Although strongly affected diagenetically, stromatolites still retain film-bounded microstructure (Grey *etal.* 1992). Very fine micritic grains occurring scattered or as small pockets inside stromatolites could represent micritized ooids, the commonest allochem in the environment where stromatolite bioherms developed (Reid *etal.* 2000). Microphytolites, though rare, are observed inside the laminations of the stromatoids.

Dissolution vugs filled with fine sediment occur on the top of the basal bioherms.

Figure 4.8a – 4.8c. Member 5 - Stromatolite dolostone

a) Basal stromatolite bioherm made up of contiguous to closely spaced pseudo-columnar to columnar stromatoids. The basal bioherms constitute barrier reefs. Location: Stromatolite dolostone member, Gão Mogol Hill.

b) Stromatolitic bioherm made up of branched stromatoids. Location: Stromatolite dolostone member, Grão Mogol Hill.

c) Nodular stromatoid growing over dolostone displaying planar cross-bedding. Location: Stromatolite dolostone member, Grão Mogol Hill.

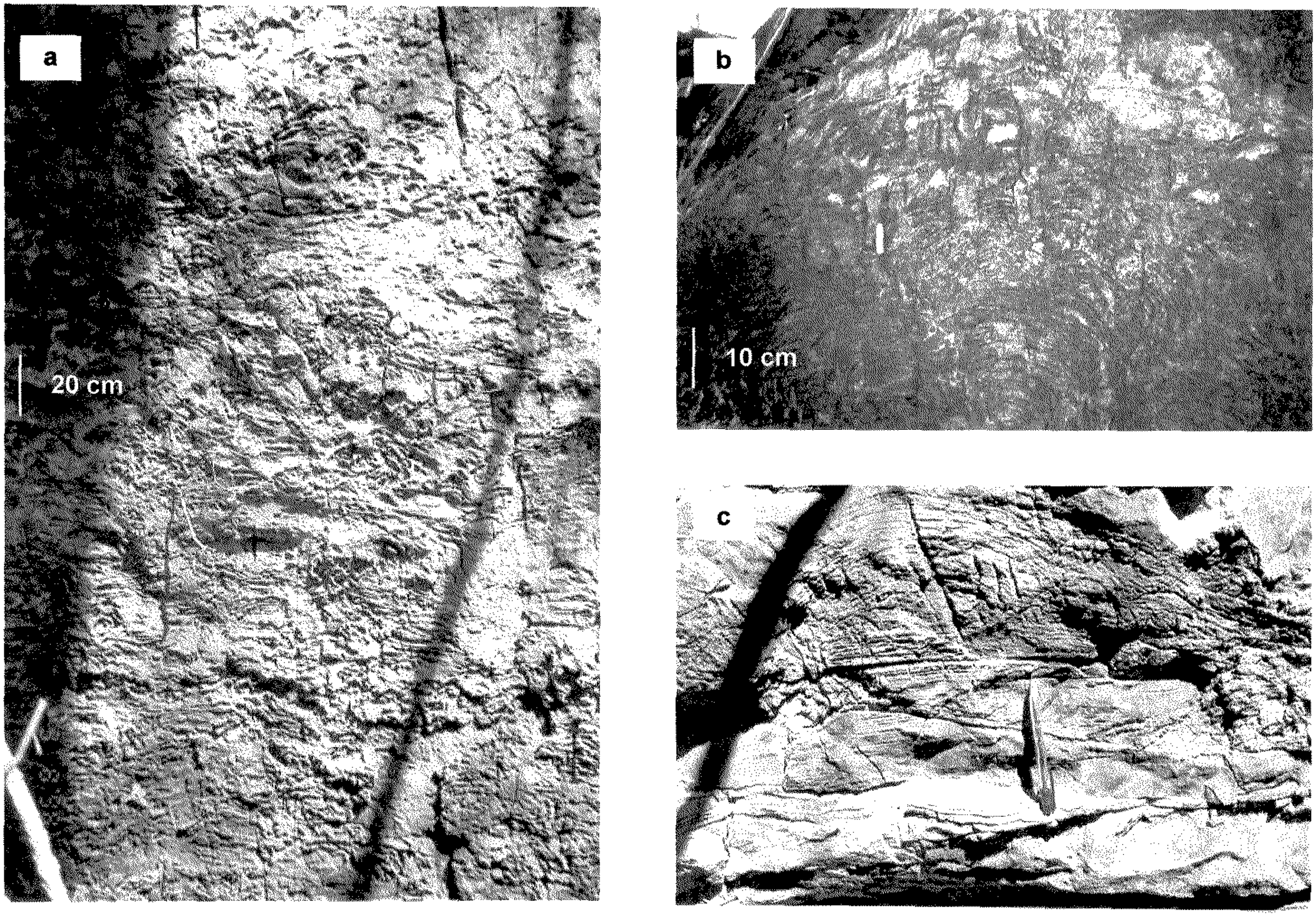


Figure 4.8. Member 5 – Stromatolite dolostone.

Dolomitization is pervasive, texturally preserving, resulting in a crypto to microcrystalline dolomite mosaic.

Non-stromatolitic dolostones

Dolomudstones are subordinate, occurring close to and behind the basal bioherms. Petrographically they are laminated dolosiltites. Dolomitization is mostly texturally preserving and constitutes a microcrystalline mosaic.

4.2.6 MEMBER 6 – OOID-INTRACLAST DOLOSTONE

Regionally widespread, the ooid-intraclast dolostone member shows significant differences in thickness, being capped by sediments of the lowermost unit (7A) of the dolomudstone member 7.

The upper limit of the member is a regionally extensive surface with local irregularities and its contact with the member stratigraphically above can be sharp or gradational. The lower limit is frequently difficult to define in the whole area because it is strongly affected by dolomitization and dissolution/collapse brecciation. The exception is where it covers stromatolite bioherms; in thist case the contact is sharp and well defined because stromatolite is hardly afected by dissolution/collapse brecciation.

Consequently, both the lower limit and the thickness of the member have not bear precisely defined. For pratical purposes the thickness of the member is considered to be approximate, and ranging between 6 m and 2 m (southwestern part of the Serra do Cantinho Hill).

The original layers are mostly destroyed by dissolution/collapse brecciation but in less affected areas remains of low-angle planar and bidirectional (herringbone-like) cross-bedding decimeter thick as well as trough cross bedding (diameter ~ 30 to 40 centimeters) are still visible (Fig. 4.9); low-angle planar cross-bedding exhibits angular foresets (dms thick). These cross-bedded remains are useful parameters to recognize macroscopically the member and help in an approximate way to evaluate its thickness.

Figure 4.9a – 4.9b. Member 6 - Ooid-intraclast dolostone

a) Outcrop showing remains of trough cross-bedding in area strongly affected by dolomitization. Location: Ooid-intraclast dolostone member, Grão Mogol Hill.

b) Close view of outcrop exhibiting remains of planar cross-bedding in area strongly affected by dolomitization. Ooid-intraclast dolostone member, Grão Mogol Hill.

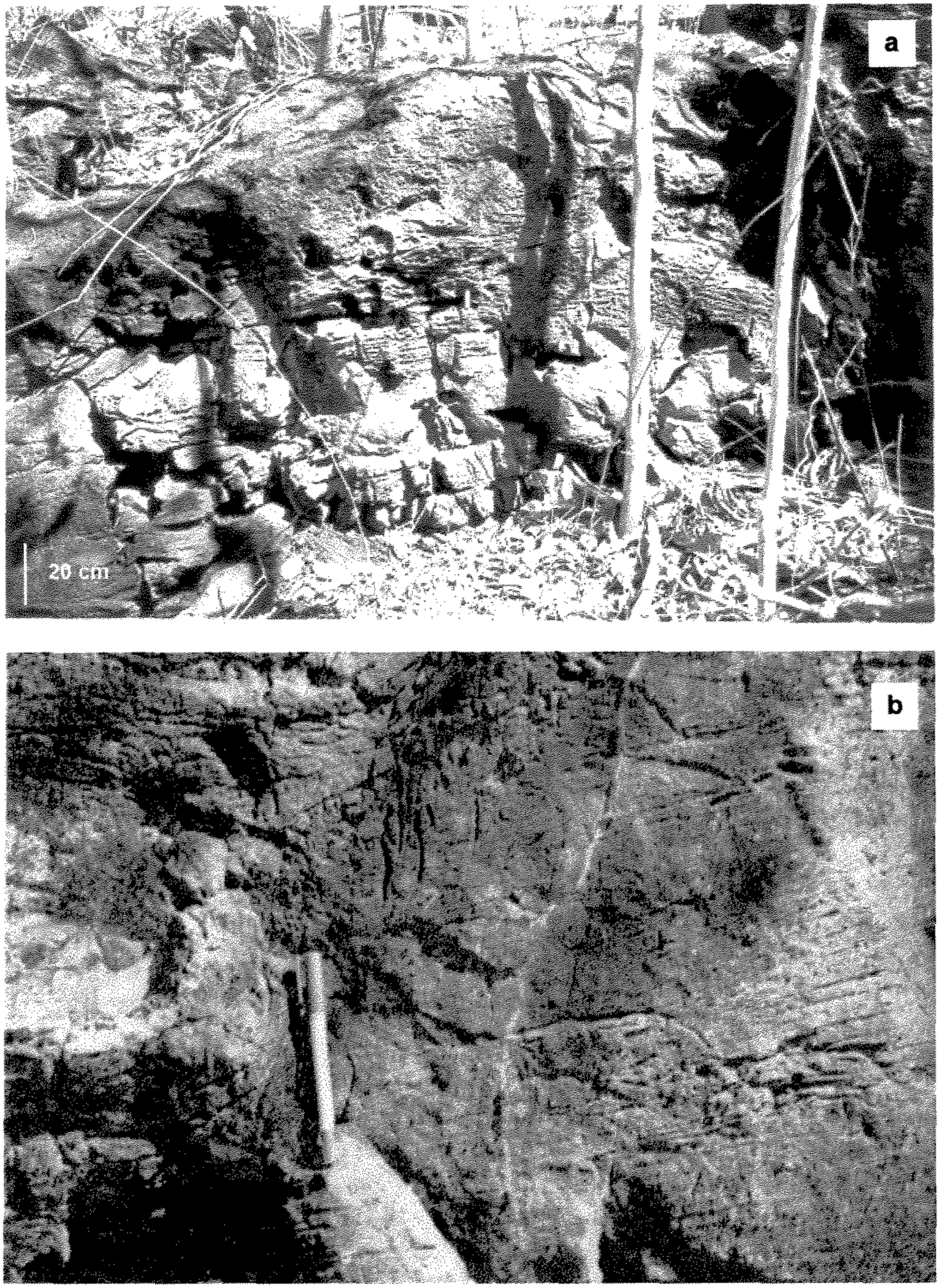


Figure 4.9. Member 6 – Ooid-intraclast dolostone.

In a vertical succession remains of trough cross-bedding occurs stratigraphically below the bidirectional cross-bedding and planar cross-bedding are always present in the uppermost part of the member. Remains of bidirectional cross-bedding was observed above a basal stromatolite bioherm.

Another characteristic of the member, defined petrographically, is the presence of intraclasts mixed with ooidal sediment (Fig. 4.10b, c); this criterium is not absolute because intraclasts can be missing.

Petrographically the ooid-intraclast dolostone member 6 is made up mainly of grainstones to packstones; packstones to wackestones are subordinate.

The main allochems are remains of ooids locally with ghosts of concentric layers (Fig. 4.10a) and intraclasts. Intraclasts can be of dolomudstone (massive, laminated or displaying grumelous texture), of fine peloidal grainstones or grains of ooidal grainstones frequently showing truncated grains. As locally remains of ooids still retain ghosts of concentric layers they will be named ooids instead pseudo-ooids.

Three main types of grainstones to packstones are described based on the granulometry and internal texture of the allochems: ooidal, mixed ooid-intraclast (medium to coarse size) and intraclast-pseudo intraclasts (mostly coarse to very coarse sand). Except for the coarser units that are lateral and vertically limited, ooidal and mixed-ooid-intraclast grainstones to packstones grade into one another.

In mixed-ooid-intraclast grainstones to packstones the average of intraclasts is highly variable though rarely dominant over ooidal grains; intraclasts are rounded to well rounded and slightly coarser than ooidal remains and coarsening upwards is common. Intraclasts were affected by a replacement dolomite texturally preserving which strongly contrasts with the coarse dolomite replacement affecting the background ooidal sediment (Figure 4.10b). Isopachous acicular rim cementation can be seen around better preserved allochems (see Fig. 5.1d).

Intraclast to pseudo intraclast grainstone to packstones are strongly affected by dolomitization, but some allochems, especially those finely dolomitized, retain at least part of the original texture (Fig. 4.10c, d). Some pseudo-intraclasts can result from diagenetic processes but others keep a disctinctive pattern that suggests they were deposited as detrital grains (Fig. 4.10c, d); ooidal interbeds can be present.

Figure 4.10a – 4.10d. Ooid-intraclast dolostone member – main petrographic types

a) Thin section photomicrograph of ooidal grainstone strongly affected by replacement dolomitization. Plane light. Location: Ooid-intraclast dolostone member, Serra do Cantinho Hill.

b) Thin section photomicrograph of mixed ooid-intraclast dolostone; ooidal grains make up the background sediment being strongly affected by replacement dolomitization. Plane light. Location: Ooid-intraclast dolostone member, Serra do Cantinho Hill.

c) Thin section photomicrograph of mixed intraclasts-pseudo intraclasts dolostones. Dolomitization strongly affects the intraclasts except those made up of dolomudstones or of reworked ooidal dolostones. Plane light. Location: Ooid-intraclast dolostone member, Serrotinho.

d) Thin section photomicrograph of mixed intraclasts-pseudo intraclasts dolostones. Allochems are strongly affected by dolomitization. Plane light. Location: Ooid-intraclast dolostone member, Serrotinho.

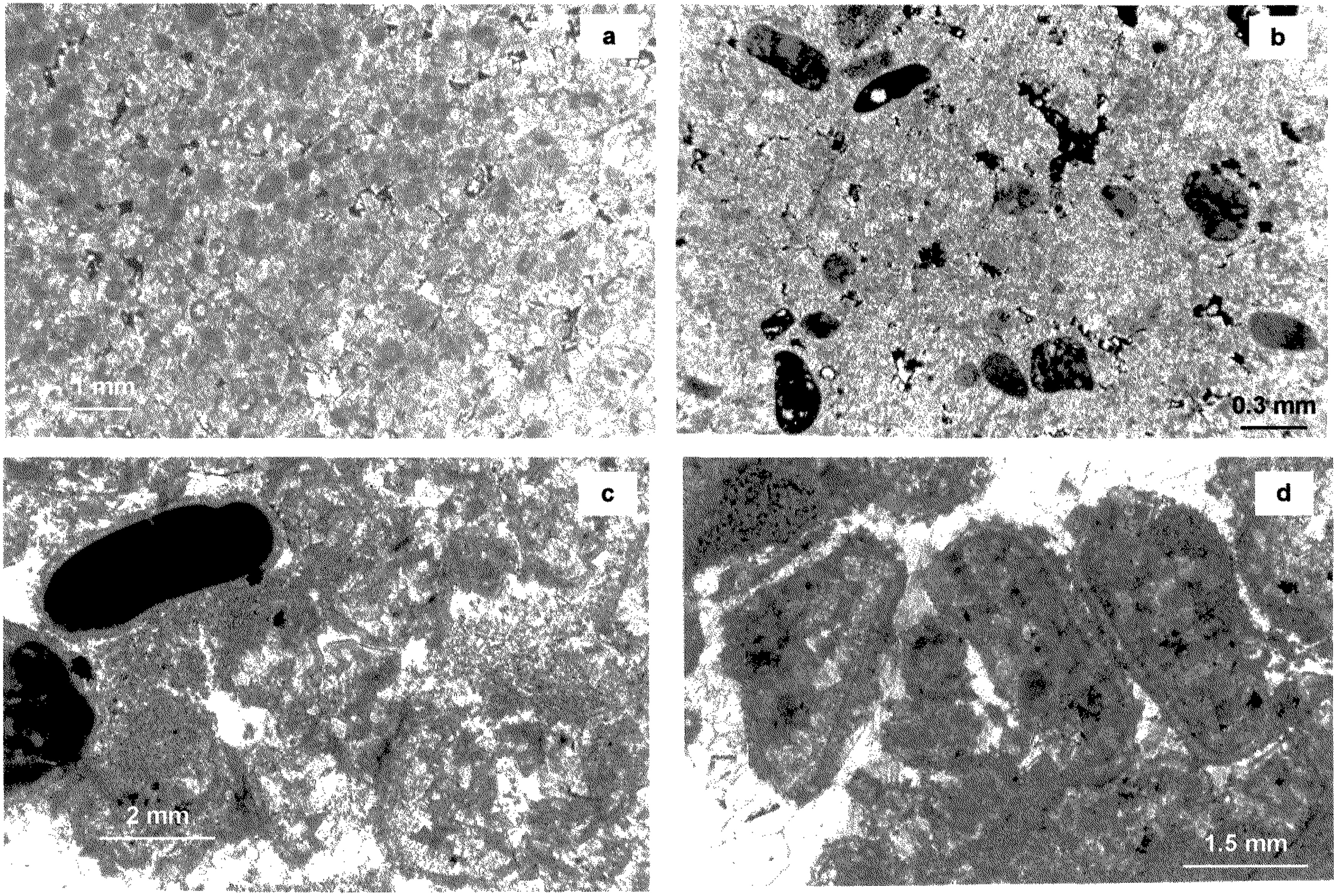


Figure 4.10. Member 6 - Ooid-intraclast dolostone – main petrographic types.

Packstones (coarse to very-coarse sand) commonly grade to wackestones defining normal grading by decrease of the intraclasts; they are observed locally in the uppermost part of the member grading to the basal unit (7A) of the dolomudstone member 7. Intraclasts are well rounded, and mostly of dolomudstone; of secondary importance are intraclasts of ooidal grainstone with truncated grains and possible grapestones.

Pervasive, texturally destructive replacement dolomitization affects the whole member; dolomite cementation is very important, filling open fractures and cavities. Sparry calcite also fills fractures and vugs.

4.2.7 MEMBER 7 – DOLOMUDSTONE

The dolomudstone member is ~ 30 meter thick and fully observed only at Grão Mogol Hill; in the remaining described sections it is only a few meters or have been completely eroded. The lower contact with the ooid-intraclast dolostone member 6 can be sharp or gradational, but in outcrop it seems sharp most of the time (Fig. 4.11a). The upper contact with the overlying pelitic sediments of the Serra de Santa Helena Formation is poorly exposed, but a hundred kilometers to the north this contact is gradational.

The whole member consists of peritidal sediments composing small shallowing-upwards successions (3 to 5 meters in thickness) bounded by erosional surfaces, and having on the top features suggesting subaerial exposure. Sedimentary environments vary from shallow subtidal to supratidal. The dolomudstone member is divided into 2 units: 7A and 7B. The unit 7A is basal, cover directly the ooid-intraclast member 6 stratigraphically below; and have on the top pronounced desiccation features. The Unit 7B includes the uppermost shallowing-upwards successions of the dolomudstone member stratigraphically above the unit 7A.

The main sedimentary structures in shallow subtidal to intertidal environments are planar-parallel bedding and low-angle cross-lamination (Fig. 4.11b); lenticular bedding, small wavy-ripples and climbing-ripple lamination are subordinate and areally restricted. In high intertidal to supratidal environment tepees and desiccation cracks are common (Fig. 4.11c); vadose micritic cements of meniscus and microstalactitic (gravitational) fabrics are common as well as small vugs displaying geopetal features (see chapter 5).

Figure 4.11a – 4.11d. Member 7 - Dolomudstone

a) Outcrop showing the lowermost contact of the Dolomudstone member (Unit 7A) with the Ooid-intraclast dolostone member (6). Location: Serra do Cantinho Hill.

b) Outcrop of dolomudstone displaying planar-parallel lamination and silicified rugged layers (succession type 4). Location: Unit 7B of the Dolomudstone member, Grão Mogol Hill.

c) Dolomudstone displaying tepee structure in high-intertidal environment (succession type 1). Location: Unit 7A of the Dolomudstone member, Grão Mogol Hill.

d) Stromatolitic biostrome made up of columnar to bulbous stromatoids; intertidal environment (succession type 4). Location: Unit 7B of the Dolomudstone member, Grão Mogol Hill.

Figure 4.11. Member 7 – Dolomudstone.

Stromatolite biostromes are common in shallow subtidal to intertidal environments (Fig. 4.11d).

The unit 7A can be correlated in the whole area though with dissimilar lithofacies association. Dolomitized fine sediments usually dominate but can also be subordinate; in that case grainy sediments dominate over dolomudstones.

Upwardss, outcrops of the basal succession of the unit 7B can be compared at Gão Mogol and Serra do Cantinho Hills; the uppermost successions were described only in the Grão Mogol Hill.

Four main types of shallowing-upwards successions were defined based on the dominant lithofacies (Figure 4.12).

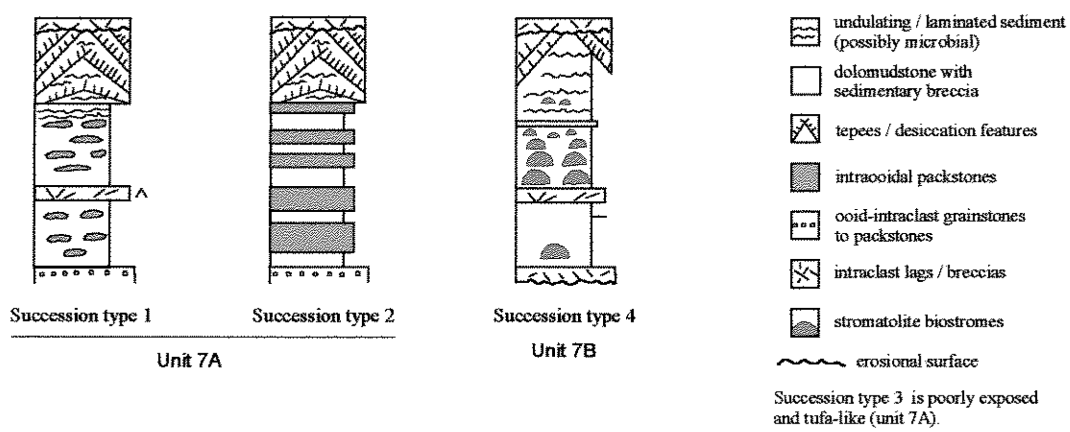


Figure 4.12. Dolomudstone member 7-main types of shallowing upward successions

Sucession types 1, 2 and 3 belonging to the unit 7A can be correlated not only because directly overlying the ooid-intraclast dolostone member 6, but also because they displays frequent interbeds made up of ooids and ooidal intraclasts with truncated grains. Succession type 4 characterizes the upper shallowing-upwards successions; oolitic horizons are no longer observed.

Succession type 1 is made up of dolomudstone with interlayers or pockets of grainy sediments and breccia displaying normal grading. Petrographically dolomudstones are finely laminated or massive dolosiltites (Fig. 4.13a); granular interbeds are of oolitic grainstones and peloidal-intraclast packstones. Meniscus and gravitacional cements are locally observed in oolitic grainstones and micritic (see Fig. 5.1c, d).

In the uppermost layers desiccation cracks and tepees are widespread. Type 1 succession was described at Grão Mogol Hill.

Type 2 succession is a mixed packstone-dolomudstone succession in which packstones dominate over dolomudstone. It was described at Serra do Cantinho Hill, in a portion devoid of important basal stromatolite bioherms (stromatolite dolostone member 5). Packstones are intrapeloidal very fine sand having scattered ooids (fine sand), and ooidal intraclasts (medium sand); interbeds are of silt to very fine sand laminated intrapeloidal wackestone (Fig. 4.13c). Layers displaying desiccation cracks and geopetal features are recurrent in the section, and the uppermost bed is capped by a pebbly intraclast lag starting the following succession.

Type 3 succcession is poorly exposed and the dolomudstone strongly brecciated; it was found only at Serra da Umburana Hill. The background sediment is dolomudstone with interbeds of ooidal sediments but the main feature is a tufa-like sediment displaying small tepee-like structures. Tufa layers developed over dolomudstone (Fig. 4.13b) as well as over ooidal interbeds.

Unit 7B is characterized by type 4 succession that represents the uppermost small-scale sucessions of the dolomudstone member 7. Commonly the succession starts with a basal lag made up of intraclasts traceable from adjacent layers that is followed by poorly or well-laminated silt-size dolomudstones.

Horizons made up of well-rounded lamelar intraclasts (packstones to grainstone fine to very coarse sand) are common; microphytolite wackestones are of secondary importance (Fig. 4.13d).

Oolitic interbeds are missing in the whole area.

Stromatolite biostromes are widespread, few decimeters thick and up to 20 meters long in outcrop; stromatoids are domal or branched (see Fig. 4.11d). Undulating and laterally continuous laminated sediments of grumelous texture are frequent in the uppermost part of the succession and display small tepees.

Figure 4.13a – 4.13 d. Member 7 – Dolomudstone: the main petrographic textures

a) Thin section photomicrograph of undulose lamination in dolomustone showing small pockets of intraclasts. Dark material on the top is diagenetic pyrite (succession type 1). Plane light. Location: Unit 7A of the Dolomudstone member, Grão Mogol Hill.

b) Thin section photomicrograph of tufa-like showing small tepee-like structures above dolomudstone (type 3 succession). Plane light. Location: Unit 7A of the Dolomudstone member, Grão Mogol Hill.

c) Thin section photomicrograph of intrapeloidal packstones with scattered ooidal grains having subordinate interbeds of dolomudstones (succession type 2). Plane light. Location: Unit 7A of the Dolomudstone member, Serra do Cantinho Hill.

d) Thin section photomicrograph of microphytolite wackestone (succession type 4). Plane light. Location: Unit 7B of the Dolomudstone member, Grão Mogol Hill.

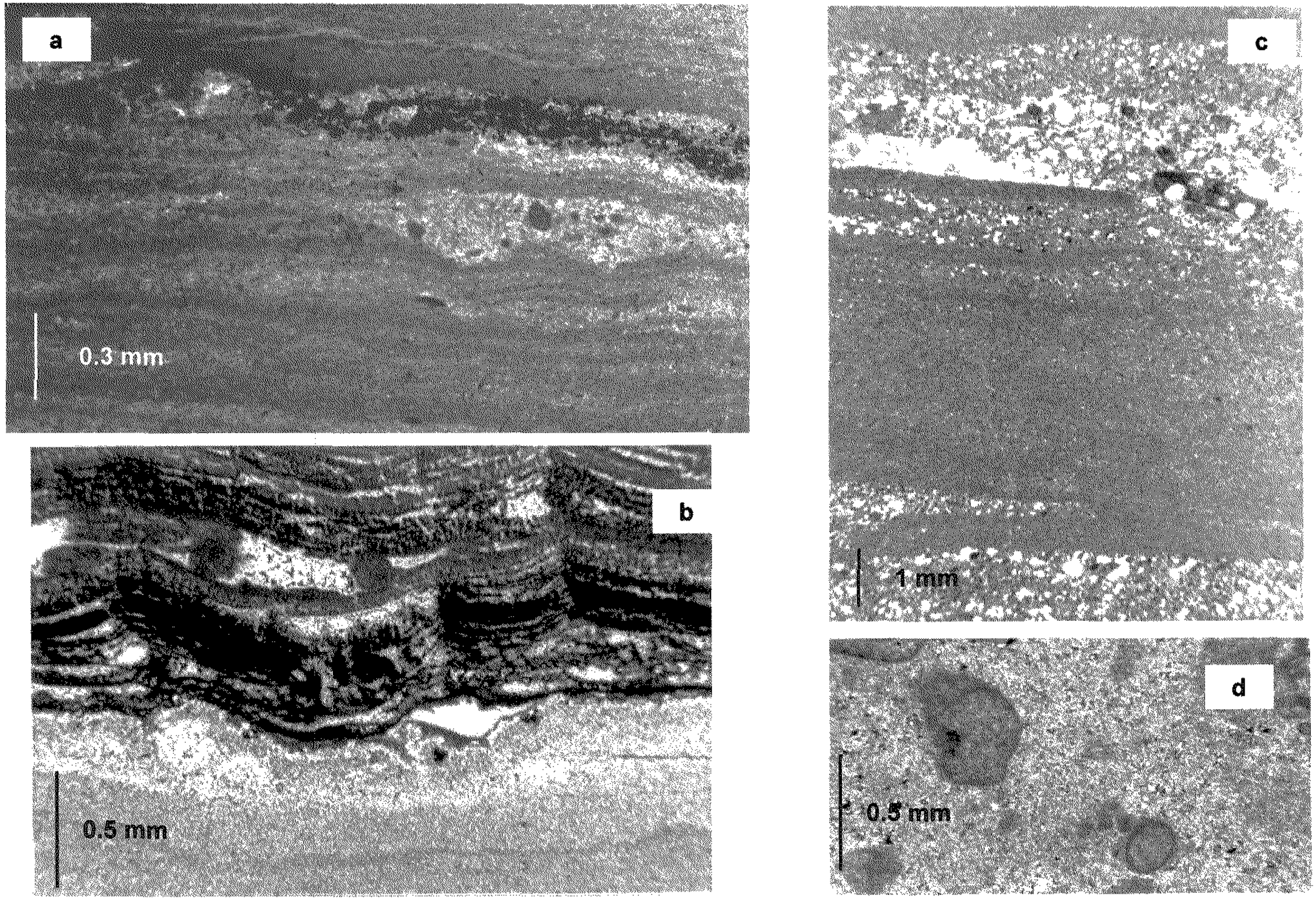


Figure 4.13. Member 7 – Dolomudstone: main petrographic textures.

Type 4 successions exhibit lateral changes as well as diversified lithofacies association and the second succession (stratigraphically above succession types 1, 2 and 3) is a good example to illustrate the variety of lithofacies association.

It always starts with a basal intraclast lag; intraclasts are traceable from the neighbouring sediments. Upwards, at Gão Mogol Hill, poorly laminated silt-size dolomudstones dominate with thin interbeds of intraclast grainstones to packstones (mostly coarse to very coarse sand); aparently stromatolite biostromes are subordinate. At Serra do Cantinho Hill a well developed biostrome (~60cm thick), made up of branched stromatoids, growth above the basal lag, and was followed by dolomudstone displaying lenticular bedding with interlayers made up of well rounded, coarse to very coarse intraclasts (grainstones to packstones) and microbreccias.

Dolomitization in the whole dolomudstone member is massive, mostly microcrystalline and represents a texturally preserving early diagenetic replacement.

4.3 INTERPRETATION

The Sete Lagoas sediments in the Januária region are interpreted to represent an extensive carbonate platform affected by growth-faults active during sedimentation. The study area had a lower subsidence rate compared to the neighbouring areas (see Chapter 2). Antecedent topography also influenced sedimentation. Thickness of the sedimentary pile thins to the southwest reflecting shallower depositional environment and consequently less accomodation space.

The Sete Lagoas Formation is informally divided into 7 members grouped into three main shallowing-upwards successions, basal, intermediate and upper successions.

The basal succession consists of two members, argillaceous lime mudstone member 1 (basal) and calcirudite member 2; a thin layer of pink dolomudstone lying over rocks belonging to the crystalline basement and described in the neighbouring areas, does not outcrop in the study area.

The intermediate succession includes the interval between members 3 (dolomitic calcarenite) to the lowermost unit of the dolomudstone member 7 (unit 7A), and the upper succession is made up of the upper unit of the member 7 (unit 7B).

4.3.1. BASAL SHALLOWING-UPWARDS SUCCESSION

In the basal shallowing-upwards succession, argillaceous lime mudstones of low-energy subtidal to intertidal environments decrease upwards, whereas calcirudites become frequent. Calcirudites are mainly rudstones, ungraded or poorly graded and represent storm sedimentation in tidal channels or intraformational sheet-like breccias in intertidal to supratidal flats.

Fine-grained detrital interbeds displaying low-angle cross-lamination similar to HCS are storm related; areally restricted, finely laminated lime mudstones closely associated with the breccia layers are interpreted as supratidal levee deposits. Tepee-like structures and desiccation crack layers suggest subaerial exposure.

This basal succession is interpreted as recording a prograding interval deposited in a low-energy carbonate platform, or a shallow shelf, where low-energy tidal flats were cut by tidal channels with supratidal levees (Figure 4.14). This lowermost shallowing-upward cycle probably records, at least in the area studied, a progradation related to the first transgression at the start of Bambuí sedimentation.

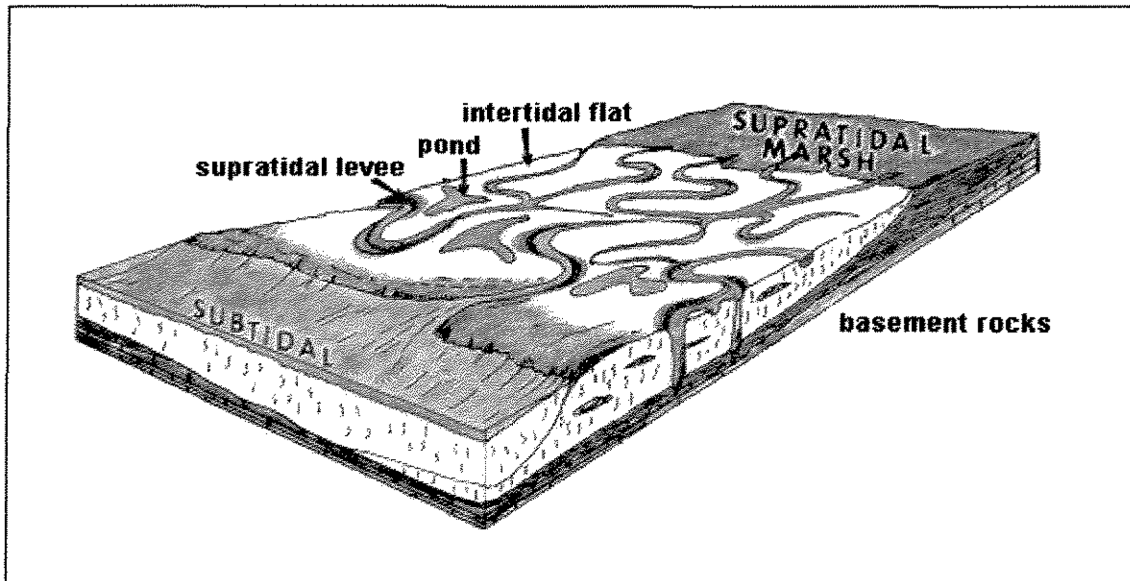


Figure 4.14. Tidal flat progradation: proposed model for the basal shallowing-upwards succession. After Shinn (1983)

4.3.2. INTERMEDIATE SHALLOWING-UPWARDS SUCCESSION

The intermediate shallowing-upward succession starts with the dolomitic calcarenite member 3, followed upwards by the dolostone, stromatolite dolostone and ooid-intraclast dolostone members (members 4 to 6), and capped by the unit 7A, the lowermost portion of the dolomudstone member 7, with desiccation features indicating subaerial esposure of the carbonate platform.

The overall interpretation is that it represents a shallowing-upwards succession from muddy to sandier sediments deposited in "offshore" through a sandier shoreface with stromatolitic reefal barrier, lagoonal and beach to tidal flat environments suggesting altogether a complex paleogeographic setting to the area (Fig. 4.15).

Storm-related sedimentation is of great importance in the whole succession but especially in the uppermost part of the dolomitic calcarenite member 3.

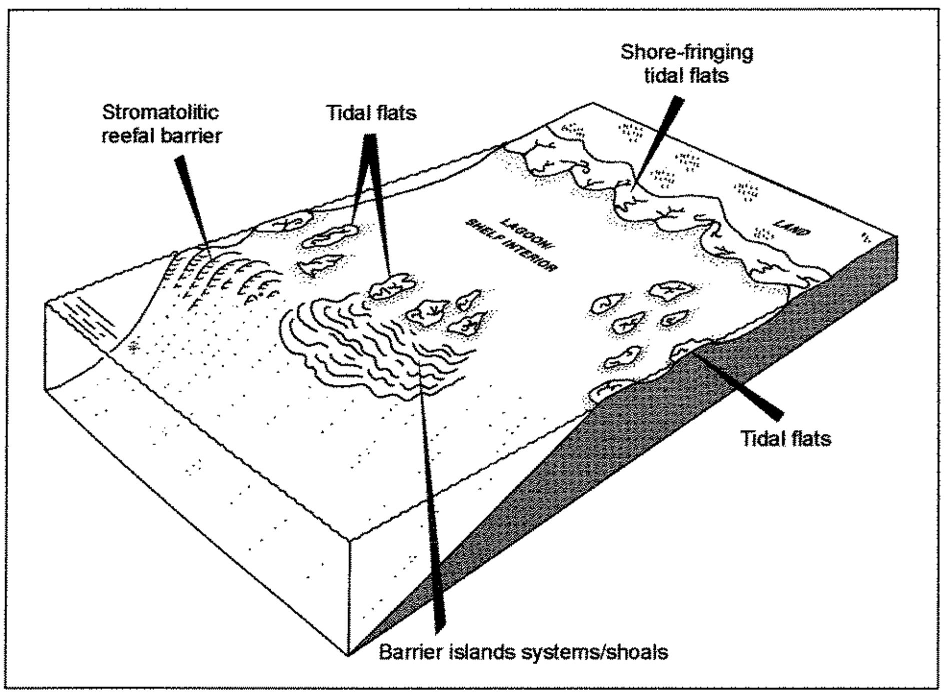


Figure 4.15. Intermediate shallowing-upwards succession: a possible model. (modified from Pratt etal. 1992)

The boundary between the lowermost and intermediate cycle records a major increase in muddy layers displaying planar-parallel bedding interbedded with thin low-angle cross-laminated interbeds (HCS); finelly laminated lime mudstones and desiccation features are no longer observed.

Overall these changes indicate a shift from a shallow, intermittently emergent environment (in basal succession calcirudite member 2) to a deeper low-energy setting in the dolomitic calcarenite member 3, below fairweather wave-base, sporadically affected by storms.

Upwards in member 3 the sediments become sandier and consist of poorly preserved ooids and intraclasts; HCS/SCS are ubiquitous and fairweather sedimentation is absent.

The depositional environment of the uppermost, sandier unit is matter of controversy. Sandbodies are mostly considered as developed in shoreface (Walker 1992; Renson 1992). Its position in offshore would be related to a later sea-level raise. However Indem and Moore (1983) consider that not only a shoreface but also an offshore environment can be sandier in high-energy shelfs.

Thus, the sandier unit displaying SCS can be considered as forming in a shelf wave and storm dominated "offshore" or on a shoreface. If it represents shoreface deposition, a short-lived, transgressive interval would be necessary to explain the sedimentary succession. For the moment the simplest solution is to interpret the sandier units as representing offshore sedimentation under storm conditions.

The pronounced change upwards in the sedimentary pattern, from units displaying HCS/SCS (dolomitic calcarenite member 3) to low-angle planar cross-bedding with multiple interbeds of large-scale rippled bedding suggest a change in the physical conditions of the environment, from a stormy period to a fairweather sedimentation. Changes in the physical conditions could also indicate deepening waters that could be related to sea-level rise affecting the member 3.

Planar cross-bedding units with tangential foresets are interpreted as resulting from wave action (Reineck and Singh 1986); the large-scale concave to sigmoidal ripples are interpreted to have formed during sporadic high tides and/or storms.

Thus, the dolostone member 4 is interpreted as representing extensive submarine sandbodies developed in shoreface, on a "shelf or platform margin", periodically affected by storms.

Local colonization of the sandbodies by microbial communities resulted in the development of the stromatolitic bioherms of member 5. The basal bioherm reached sea-level and were intermittently exposed. They represent a reefal barrier with prominent relief (at least 3 to 7m high) developed close to or at "shelf margin break". Reefal barriers on shelf break margins usually develop during highstand sea-level (James and Mountjoy 1983).

Stromatolite barrier reefs isolate different types of shelf lagoons in back-reef. Lagoons are either restricted or show features of more open circulation depending on whether the stromatolitic reef was continuous (e.g. some areas of Serra do Cantinho Hill) or not (as in Grão Mogol Hill). In the soutwestern area stromatolites are very subordinate or missing. Barrier islands and/or shoals also could be responsible for low-energy environments along parts of the shoreline.

The dolostone member 4 and the stromatolite dolostone member 5 are interpreted as developing during a sea-level highstand.

Stratigraphycally above, the ooid-intraclast dolostone member 6 contains remains of trough, bidirectional and low angle planar cross-bedding, commonly associated with beach environment and also to barrier islands systems and tidal channels (Indem and Moore 1983; Tucker and Wright 1990).

Sediments are ooidal, similar to those observed in the dolostone member 4. In addition, coarser intraclasts (coarse to very coarse sand) mixed with ooids show evidence of beachrock cementation as shown by the isopachous rin cementation of acicular crystals around allochems suggesting deposition in a foreshore environment (Indem and Moore 1983).

Some intraclasts exhibit truncated grains that are interpreted as reworked beachrock slabs resulting from storm action. The presence of a restricted, lagoonal environment is indicated by the presence of low-energy packstones to wackestones.

Coarser sand units made up of intraclast to pseudo-intraclasts grainstones to packstones lack sedimentary structures, are laterally limited and interpreted as possibly tidal inlets. Eolian sediments were not identified.

Altogether these evidences suggest that the sediments of the dolostone and ooid-intraclast dolostone members (4 and 6) represent a continuum of shallower environments, from shoreface to foreshore, under tidal influence in an extensive shallow marine shelf sporadically affected by storms. The main environments present are interpreted to be beach, possibly island barrier systems (?), lagoons and tidal channels.

The ooid-intraclast dolostone member 6 records a prograding phase in the carbonate platform development that is overlain by low-energy tidal flats represented by the unit 7A, the lowermost unit of the dolomudstone member 7.

As reefal barriers are common along a shoreface, as well as around barrier islands, coastal environments would be mostly low-energy beaches that would grade into and be overlain by low-energy tidal flats (Indem and Moore, 1983), as accomodation space of the lagoons and tidal flat was filled.

The contact between the ooid-intraclast dolostone and dolomudstone members (6 and 7) is either sharp or transitional recording environmental changes from inferred low-energy beaches to prograding tidal flats.

Gradation between members 6 and 7 (unit 7A) is common where tidal flat prograde over lagoonal sediments; sharp contacts occur where sandier, foreshore units, were covered by fine sediments. Tufa-like sediments always display sharp contact.

The presence of abundant oolitic interbeds restricted to the unit 7A stratigraphically above the ooid-intraclast dolostone member 6, indicate continuity of sedimentation between members 6 and the lowermost unit (7A) of the dolomudstone member 7.

The lowermost unit (7A) of the dolomudstone member records shallow subtidal to supratidal sedimentation. Subtidal sediments diaplay planar-parallel and low-angle cross-lamination; evidence for intertidal environments includes numerous interbeds of oolitic and intraclastic facies, tepees and vadose diagenetic micritic meniscus and gravitacional cements are common. Supratidal environments also display layers with desiccation cracks. Tufa sediments indicate environment under meteoric influence "landward", of supratidal zones.

Thus, the lowermost unit (7A) of the dolomudstone member 7 records tidal flat progradation followed by subaerial exposure of the carbonate platform consisting of widespread vadose cementatin, tepees and desiccation cracks that ended the intermediate shallowing-upwards succession.

4.3.3. UPPER SHALOWING-UPWARDS SUCCESSION

The upper unit (7B) of the dolomudstone member form the uppermost or third shallowing-upwards succession. These beds record low-energy peritidal carbonate succession a few meters thick and having a stacked asymetric pattern of facies ABC>ABC (Fig, 4.16).

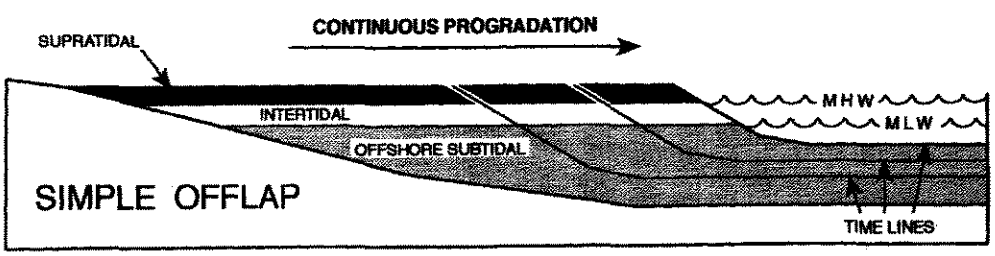


Figure 4.16. Tidal flat progradation: proposed model for the uppermost small shallowing-upwards successions making up the Unit 7B of the Dolomudstone member. After Pratt etal. (1992).

Commonly peritidal succesions start with a basal, transgressive lag that is overlying by shallow subtidal silt-sized sediments displaying planar-parallel lamination and/or subordinate low-angle cross-lamination. These intervals are interpreted as representing shallow subtidal to low intertidal environments based on the presence of planar-parallel lamination, the scarce intraclast beds and absence of vadose features.

Stromatolite biostromes developed in very shallow waters (water depth would be of few decimeters to a meter) in subtidal to intertidal environment; some biostromes exhibit discrete features suggesting intermittent subaerial exposure.

Micritic dolostones with undulating and laterally continuous lamination display small tepees, and are interpreted as microbial mats developed in high intertidal environments.

Small tepees, scarce mud cracks and small vugs containing geopetal features define the top of the shallowing-upwards cycles that are overlain by trangressive lags or shallow subtidal sediments, up to the next sedimentary succession.

Thus, the uppermost succession is interpreted as representing a series of prograding tidal flat successions recording low-energy environments ranging from shallow subtidal to high-intertidal/supratidal.

The increase in pelitic sediments upwards in the overlying Serra de Santa Helena Formation shut down the carbonate platform.

The three main successions altogether are interpreted to be a parassequence set of progradational stacking pattern, where sediments of each parasequence become progressively shallower and more proximal higher in the succession.

The main shallowing-upwards successions, lithofacies and main sedimentary structures are summarized in the Figure 4.17.

4.4 SUMMARY INTERPRETATIONS AND CONCLUSIONS

The Sete Lagoas sediments in the middle São Francisco valley are interpreted to represent an extensive carbonate platform affected by growth-faults active during sedimentation. The Januária region had a lower subsidence rate compared to the neighbouring areas (see Chapter 2). Antecedent basement topography also influenced sedimentation. Thickness of the sedimentary succession thins to southwest reflecting shallower depositional environments.

The Sete Lagoas Formation is informally divided into 7 members grouped into three main shallowing-upwards successions, basal, intermediate and upper successions.

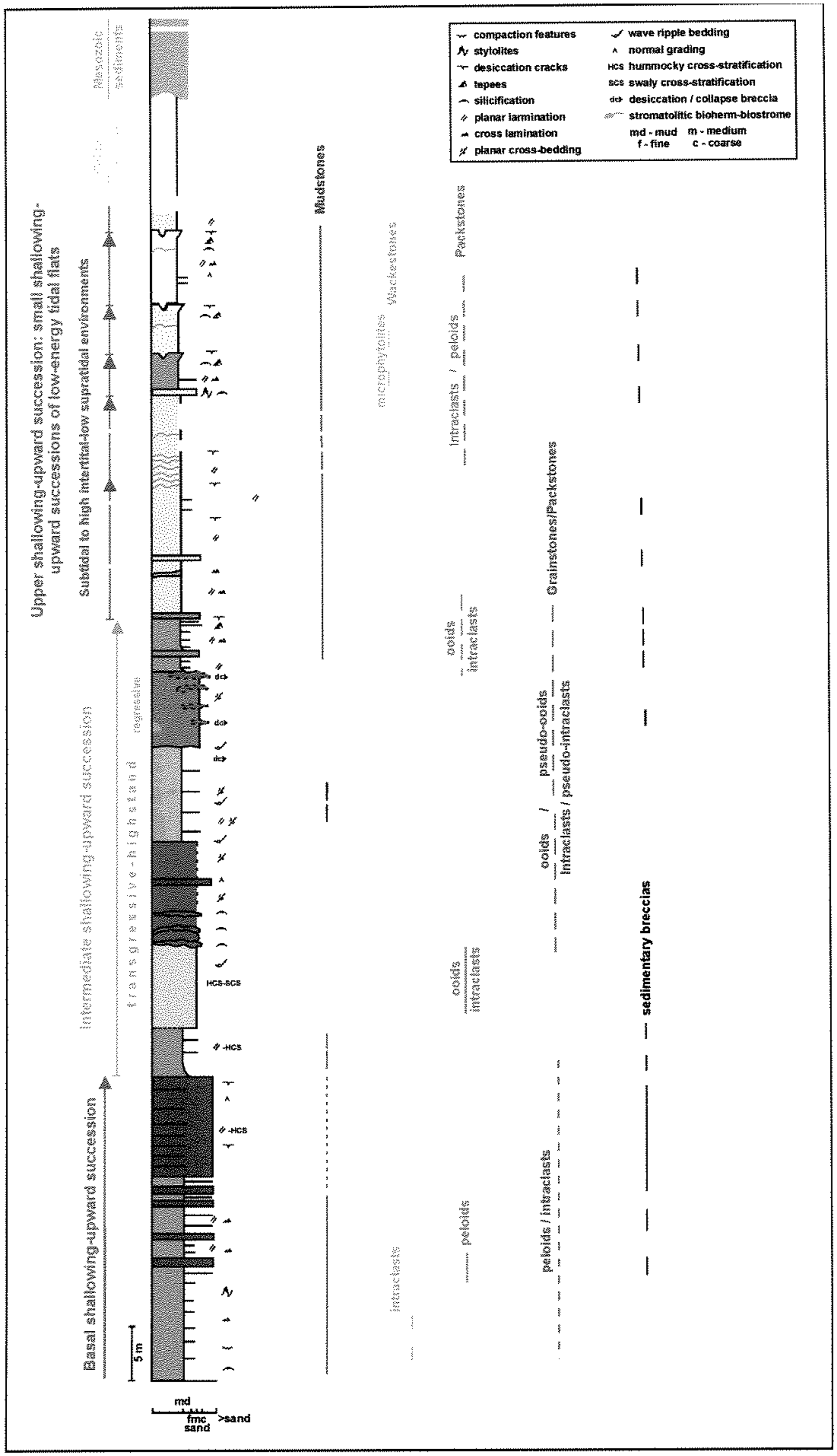


Figure 4.17. Carbonate successions at Januária region, main lithofacies and sedimentary structures. Section-type: Grão Mogol Hill.

The basal succession consists of two members 1 and 2; a thin, basal layer of pink dolomudstones lying over rocks belonging to the crystalline basement and described in the neighbouring areas does not outcrop in the study area.

The intermediate succession includes the interval between members 3 to the lowermost unit of the member 7 (unit 7A), and the upper succession is made up of the upper unit of the member 7 (unit 7B).

In the basal shallowing upward succession, argillaceous lime mudstone of low-energy subtidal to intertidal environment decreases upward whereas calcirudite become frequent. Calcirudites are mainly rudstones and are interpreted as storm deposition in tidal channels or intraformational sheet-like breccias in intertidal to supratidal flats. Detrital interbeds displaying low-angle cross-lamination are storm related. Finely laminated sediments closely related to breccia layers are interpreted as supratidal levee deposits. Tepee-like structures as desiccation crack layers suggest subaerial exposure.

Thus, the basal shallowing upward succession (members 1 and 2) is interpreted as recording a prograding interval deposited on a low-energy carbonate platform or a shallow shelf, where tidal flats were cut by tidal channels with supratidal levees, affected by storms and intermittently exposed. This lowermost shallowing upwarf cycle probably records, at least in the study area, the first transgression at the start of Bambuí sedimentation.

The boundary between the basal and intermediate succession (between members 2 and 3) records a major increase in muddy layers displaying planar-parallel bedding interbedded with HCS. Desiccation features are no longer observed.

Overall these changes indicate a shift from a shallow, intermittently emergent environment (member 2 in basal succession) to a deeper low-energy setting in member 3 below fairweather wave-base.

Upwards in the member 3 sediments become sandier and consists of poorly preserved ooids and intraclasts, HCS/SCS are ubiquitous and there is no record of fairweather sedimentation. The depositional environment of the sandier unit is matter of controversy, because sandbodies are mostly considered as developed in shoreface, and its position in offshore would be related to a sea-level raise, but an offshore environment could also be sandier in high-energy shelfs. For the moment, the simplest solution is to interpret the sandier unit of member 3 as representing offshore sedimentation under stormy condition.

The pronounced change upwards, from units displaying HCS/SCS (member 3) to low-angle planar cross-bedding with interbeds of rippled bedding indicate a change in the environment, from a stormy period to a fairweather sedimentation. Changes in the physical conditions also indicate deepening waters that could be related to a sea-level rise affecting the member 3. The dolostone member 4 is interpreted as representing extensive submarine sandbodies developed in shoreface, on a "shelf or platform margin", periodically affected by storms.

Colonization of the sandbodies by microbial communities resulted in the development of the stromatolite biohers (member5) that reached the sea-level, being intermittently exposed. They represent a reefal barrier with prominent relief developed close to or at the "shelf margin break". Stromatolite barrier reefs isolate different types of shelf lagoon in back reef depending on whether the stromatolitic rim was continuous or not. Barrier islands and/or shoals also could be responsible for low-energy environments along the shoreline.

The dolostone and stromatolite dolostone members (4 and 5) are interpreted as developed during a sea level highstand.

Stratigraphically above, the ooid-intraclst dolostone member 6 contains remains of trough, bidirectional and low-angle planar cross-bedding, commonly associated with beach environment but also to barrier islands systems and tidal channels. Sediments are ooidal and similar to those observed in the dolostone member 4; in addition, coarser intraclasts mixed with ooids show evidence of beachrock cementation. Some intraclasts exhibit truncated grains interpreted as beachrock slabs resulting from storm action. The presence of a restricted, lagoonal environment is indicated by the occurrence of packstones to wackestones.

Coarser sand units lack sedimentary structures, are laterally limited and interpreted as tidal inlets. Eolian sediments were not identified.

The ooid-intraclast member 6 records a prograding phase in the carbonate platform development that is overlain by low-energy tidal flats (lowermost unit of the member 7), as accomodation space of the lagoons and tidal flats was filled.

The contact between the ooid-intraclast dolostone member 6 and the lowermost unit (7A) of the dolomudstone members 7 is either sharp or transitional and records environmental changes from inferred low-energy beaches to prograding tidal flats. Gradation occurs where tidal flat prograde over lagoonal sediments and sharp contacts where sandier, foreshore units were covered by fine sediments.

The presence of abundant oolitic interbeds restricted to the unit 7A, imediatelly above the ooid-intraclast dolostone member 6, indicates continuity of the sedimentation between member 6 and the lowermost unit (7A) of the member 7.

The lowermost unit (7A) of the dolomudstone member 7 records shallow subtidal to supratidal sedimentation having on the upermost beds pronounced desiccation features.

Thus, the unit 7A records tidal flat progradation followed by subaerial exposure of the carbonate platform that ended the intermediate shallowing-upward succession.

The upper unit (7B) of the dolomudstone member 7 form the uppermost shallowing upward succession and records low-energy peritidal carbonate successions few meters thick. Commonly peritidal successions start with a basal, transgressive lag that is overlain by shallow subtidal fine sediments with thin dolomite intraclast horizons; stromatolite biostromes are also present and may diplay discrete desiccation features. These intervals are interpreted as representing shallow subtidal to intertidal environments.

Small tepees, rare mud cracks and small vugs containing geopetal features define the top of the small shallowing-upward cycles that are overlain by transgressive sediments of the next sedimentary succession.

The uppermost succession is thus interpreted as representing a series of prograding tidal flat successions that record low-energy environments from shallow subtidal to high intertidal/supratidal.

The increase in pelitic sediments upwards in the overlying Serra de Santa Helena Formation shut down the carbonate platform.

The three main succession altogether are interpreted to be a parasequence set of a progradational stacking patterns, where sediments of each parasequence become successively shallower and more proximal upwards in the succession.

CHAPTER 5

DIAGENETIC PARAGENESIS

The carbonate rocks of Januária region have undergone a complex history of alteration especially in subaerial and subsurface environments. Meteoric waters affected the uppermost part of the stromatolitic reef-barrier and tidal flat successions during exposure. During burial, basinal and hydrotermal fluids strongly alter members 4, 6 and the lowermost part of the member 7.

The diagenetic features are presented and discussed in order of their paragenetic sequence (Table 5.1). Overlapping phases are listed according to their first appearance.

The diagenetic features of the carbonate rocks of the Januária region are described herein for the first time, with emphasis on the diagenesis of the dolomitized and mineralized interval comprising the members 4 to 7a. This provides additional information and constraints on the origin and timing of dissolution, dolomitization, and mineralization.

The petrography and spacial distribution of the dolomites are presented entirely in Chapter 6, and therefore are not repeated here. The dissolution features affecting dolostones that host mineral deposits are outlined and discussed in Chapter 7 and only a brief description is provided in this chapter.

5.1 SUBAERIAL DIAGENESIS

DESICCATION FEATURES: Tepee-like structures and incipient tepees are observed in lime mudstones of member 2 (see Fig. 4.4c and 4.11c).

Desiccation cracks (Fig. 5.1a) and tepees are widespread in microbially laminated dolostones, dolomudstones and tuffa layers of high intertidal-supratidal environments of member 7.

Table 5.1. Diagenetic paragenesis of carbonate rocks in Januária region based on field and petrographic studies.

DIAGENESIS	EARLY → LATE
Subaerial dissolution	--- ---
Isopachous rim cementation	---
Internal sediments in cavities	---
Vadose cements	----
Anhydrite	-
Early replacement dolomites	-----
Compaction/stylolitization	--- --- --- --- --- --- --- --- --- --- --- ---
Fine dolomite associated with stylolites	--
Late replacement dolomites	------
Silicification	- --- --
Fracturing/burial dissolution	--- --- --- --- --- --- --- --- --- ---
Very coarse-crystalline dolomite (VcCD)	---
Blocky sparry cements	--- ?-?
Rhombohedral saddle dolomite	--- ---
Very finely crystalline dolomite (VfCD)	---
Zn/Ag mineralization	-----
Iron oxides	--
White saddle dolomite	--
Anhedral dolomite	--
Late-stage calcite	---
Fluorite	-
Bitumen	- - ---

Tectonic fracturing, subaerial exposure, dissolution and silicification occurred during the Mezosoic.

DISSOLUTION VUGS: Small (mm to cm) and vertically elongated cavities filled with fine sediment occur at the top of the basal stromatolite bioherm suggesting that intermitent emergence of the stromatolitic barrier (intertidal zone) caused dissolution on the uppermost part of the stromatolite buildup.

These vugs extend few centimeters below the top of bioherm and are filled by very finely crystalline dolomite (Fig. 5.1b). Dissolution vugs also occur in dolomudstones in high intertidal to supratidal areas of member 7, and are filled by ooidal and/or fine intraclastic sediments as well as by very finely crystalline dolomite.

VADOSE DOLOMITIZED CEMENT: Vadose cement was observed in oolitic sediments of the lowermost tidal flat succession of the dolomudstone member. Microstalactitic and grain-contact meniscus cement are micritic and common (Fig. 5.1c and d, respectively).

5.2 SUBMARINE DIAGENESIS

FIBROUS DOLOMITIZED CEMENT: Fibrous crystals possibly of aragonite cement are mimically replaced by dolomite. This is characterized by an isopachous rim cement of thin fibrous crystals (36μm) radiating from the boundaries of allochems. It occurs around well-preserved allochems of member 6, the ooid-intraclast dolostone member (Fig. 5.1e), and is non-luminescent. Fibrous dolomitized cement is very similar to beachrock cementation.

ANHYDRITE: Anhydrite crystals are rare and observed only in thin section. It consists of acicular, possibly primary, very finelly crystalline and semi-transparent crystals. It occurs scattered in muddy sediments filling intercolumnar spaces in intertidal stromatolites of the dolomudstone member and presumably is related to evaporative environment.

Figure 5.1a –5.1e Subaerial and submarine diagenesis

a) Desiccation cracks affecting dolomudstone. Open spaces filled by calcite cement. Subaerial diagenesis. Plane light. Location: Unit 7A of the Dolomudstone member 7, Grão Mogol Hill.

b) Dissolution vugs on the top of the stromatolitic bioherm filled with fine sediments. Subaerial diagenesis. Plane light. Location: Stromatolite dolostone member 5, Grão Mogol Hill.

c) Microstalactite vadose cement in ooidal grainstone. Cement is micritic and the rest of pore spaces are filled with dolomite cement. Plane light. Location: Unit 7A of the Dolomudstone member 7, Grão Mogol Hill.

d) Grain-contact meniscus cement (vadose cementation) in ooidal grainstone; cement is micritic and the rest of pore spaces are filled with dolomite cement. Plane light. Location: Unit 7A of the Dolomudstone member, Grão Mogol Hill.

e) Submarine diagenesis: isopachous rim of fibrous crystals, possibly of aragonite cement, mimetically replaced by dolomite; suggests beachrock cementation. Plane light. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill

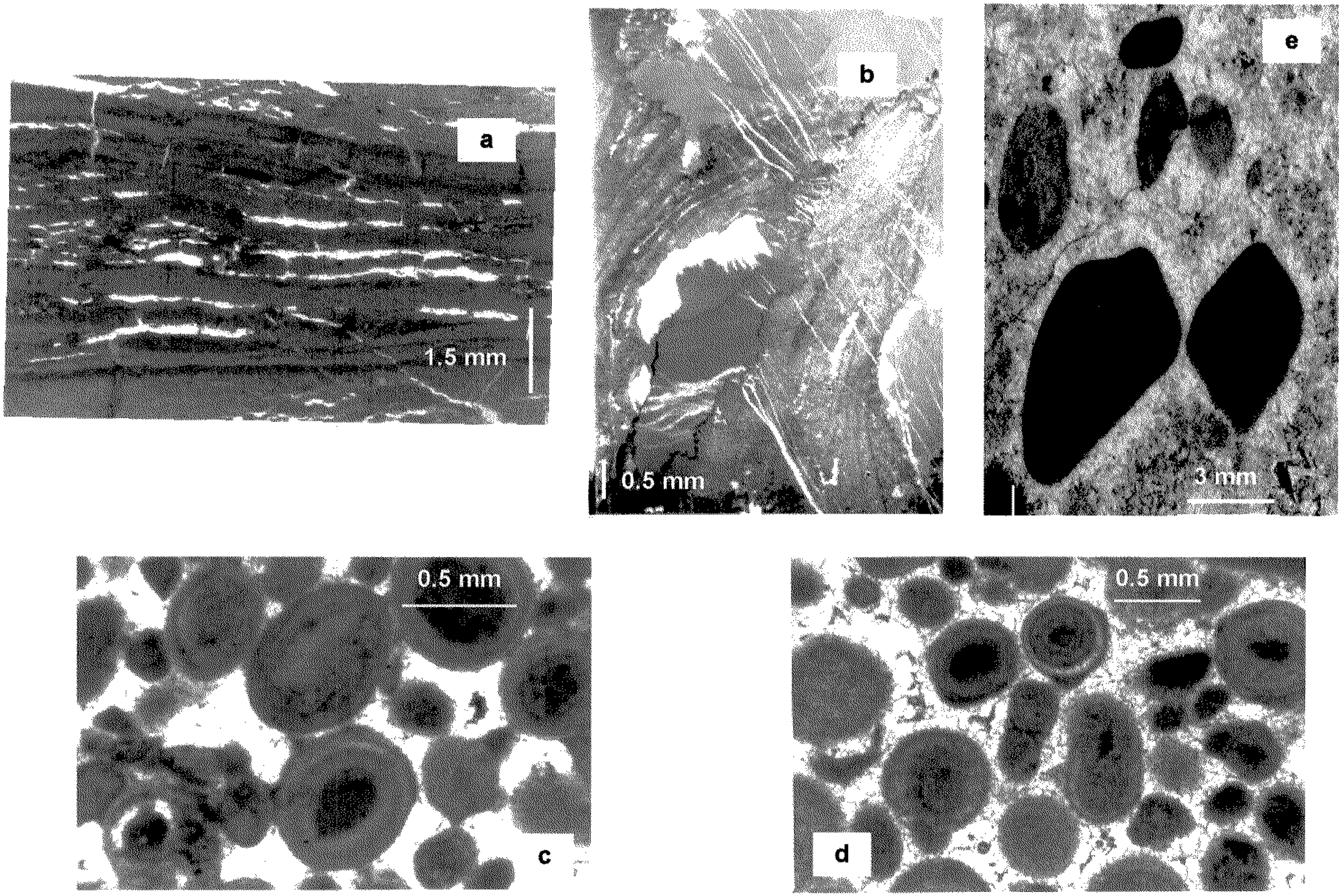


Figure 5.1. Subaerial and submarine diagenetic features.

5.3 SUBSURFACE DIAGENESIS

BLOCKY SPARRY CEMENT: Blocky sparry calcite cements form limpid, equant coarse prismatic crystals (200 to 1500 μm) that are frequently poikilotopic. They postdate fibrous cement and coarse dolomite cement, filling the remaining pores in replacement dolostones; and where poikilotopic they cement very fine euhedral dolomite rhombs (Fig. 5.2a). Most blocky sparry cement is ferroan and non-luminescent but non-ferroan blocky sparry cement has brigh-orange medium luminescence. Blocky sparry cements are affected by late, high amplitude stylolites.

PRISMATIC SPARRY CEMENT: Forms limpid to translucent crystals (414 μm long to 27 μm wide) filling small fractures that postdate late stylolite (Fig. 5.2b). It is ferroan and non-luminescent.

COMPACTION AND STYLOLITIZATION: With increasing burial, mechanical compaction is gradually overlapped by chemical compaction and stylolites (mainly microstylolites or wispy stylolites) as result of pressure dissolution (Fig. 5.2c).

Stylolites in chalk first appear at burial depths greater than ~ 470m (Lind 1993), but limestones and dolostones of the Great Bahama Bank do not exhibit compaction features at similar depths (Melim 1999). Dolomites, due to their greater resistance to pressure solution, probably formed at burial depths greater than about 1000m, thus indicating transition from shallow-burial (pre-stylolite) to intermediate burial diagenetic settings. They continue to form during progressive burial.

Early stylolytes are commonly observed in lime mudstones, wackestones and packstones. They are at least contemporary with coarse replacement dolomite: some coarse dolomite crystals exhibit corroded contours where bordered by stylolites. Also coarse crystals clearly grows over early stylolites (Fig. 5.2d). Dissolution seams (Bathurst 1987) are very rare (see Fig.4.3c).

Figure 5.2a-5.2d Subsurface diagenetic features

a) Blocky sparry calcite cement: fills vugs in the replacement dolostone, cementing also dolomite cement fringe. Plane light. Location: Dolomudstone member 7 (unit 7A), Grão Mogol Hill

b) Prismatic sparry calcite cement: fills small fractures affecting saddle rhomboedral dolomite and late stylolite. Plane light. Location: Dolomudstone member 7 (unit 7A), Serra do Cantinho Hill.

c) Compaction and early stylolitization: horizontal microstylolites are wispy or forming a network in argillaceous lime mudstone. Plane light. Location: Argillaceous lime mudstone member 1, Bom Jantar Hill.

d) Compaction and early stylolites: horizontal microstylolite affected by replacemen dolomitization; coarse dolomite crystals are clearly growing over early stylolites. Plane light. Location: Dolostone of the uppermost part of the dolomitic calcarenite member 3, Grão Mogol Hill.

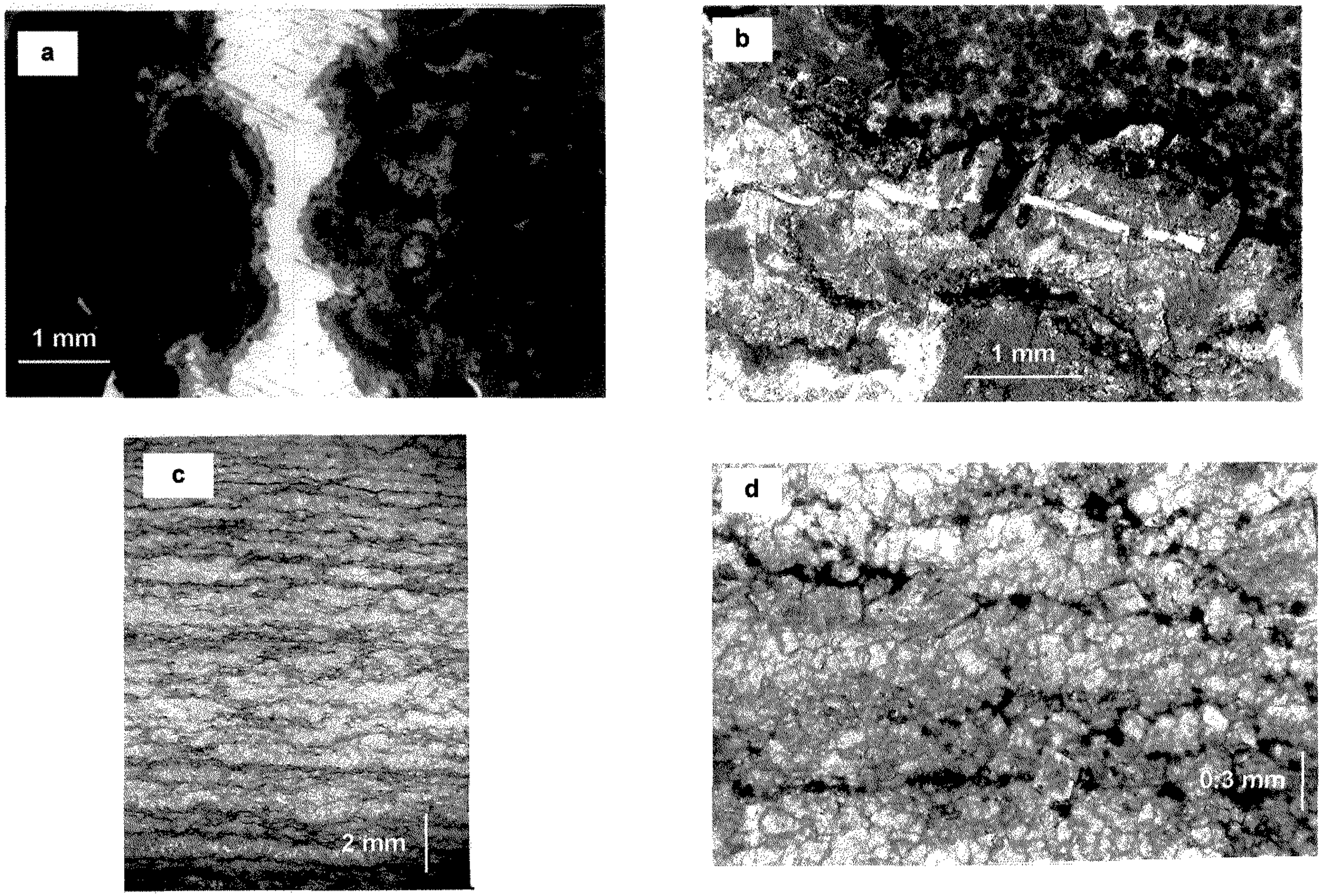


Figure 5.2. Subsurface diagenetic features.

Late stylolites always appear to have dark residual material, probably iron oxides, organic material or insolubles (see Fig. 5.2b). They mostly have high amplitudes, display high angles with the bedding and occur more frequently in and around mineralized areas but are also observed in barren areas; late stylolites also affect tidal flat lithologies. Presumably these high angle stylolites were due to horizontal stresses that developed during the formation of local structures or regional tectonic events.

SUBSURFACE DISSOLUTION: Dissolution features are described and discussed in Chapter 7. The region was invaded by basin-derived warm, acidic fluids resulting in extensive dissolution and dissolution/collapse breccias, with locally poorly defined vugs and zebra textures (Fig. 5.3a). These vugs, open fractures and collapse cavities are filled with saddle dolomite and other late diagenetic products such as sulfide minerals, pyrobetumen, quartz, late-stage calcite and fluorite (Fig. 5.3b).

Dissolution, brecciation, and associated saddle dolomite crosscut the boundaries between the ooid-intraclasts dolostone and dolomudstone members. Thus, subsurface dissolution and brecciation has occurred after deposition of the dolomudstone member and cannot be related to a hypothetical subaerial exposure (Dardenne 1979) with meteoric karst development (Lopes 1979) affecting the ooid-intraclast dolostone member.

SULFIDE AND SILICATE ORE MINERALS: The paragenetic sequence of sulfide minerals in the Januaria region is not well stablished and a simplified sequence was outlined and discussed in Chapter 3. Dark and honey sphalerite are silver-rich, usually crystalline and contain small oil inclusions; definitive replacement textures were not observed. Willemite occurs as solid inclusions in the sphalerite or as acicular crystals. Sphalerite fills open-spaces in the medium/coarse replacement dolostone cementing also breccia fragments made up of replacement dolostone and rhombohedral saddle dolomite (Fig. 5.3c); acicular willemite line vugs in brecciated dolostone having rhombohedral saddle dolomite (Fig. 5.3d). Both minerals occur mainly in the ooid-intraclast dolostone member 6 but brecciated dolomudstones (member 7) are also mineralized. Sphalerite and willemite are iron-poor, precipitated after rhombohedral saddle dolomite and overlapped with white saddle dolomite containing iron oxide solid inclusions.

Figure 5.3a-5.3d Hydrothermal dissolution and sulphide/silicate ore mineral

a) Hydrothermal dissolution generating feature similar to zebra texture in dolostone; open spaces are filled with late calcite affecting dolomite cement. Plane light. Location: Dolomudstone member 7, Serra do Cantinho Hill.

b) Hydrothermal dissolution in several steps. 1: dissolution affects replacement dolostones; vugs are filled with rhombohedral saddle dolomite; 2: hydrothermal dissolution create new porosity over replacement dolostones but also over prior saddle dolomite; vugs are filled of white saddle dolomite displaying geopetal feature; remaining porosity are filled with oil, now bitumen. Plane light. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill.

c) Sulphide ore mineral, sphalerite (dark and honey varieties) filling open-spaces in brecciated dolostone. Remains of rhombohedral saddle dolomite (arrow) affected by sphalerite and late calcite. Plane light. Location: Ooid-intraclast dolostone member 6, Imbuzeiro mine at Serra do Cantinho Hill.

d) Hydrothermal dissolution vug lined by zinc silicate in dolostone prior affected by dissolution and rhombohedral saddle dolomite cementation. Bitumen occluded the remaining porosity. Plane light. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill.

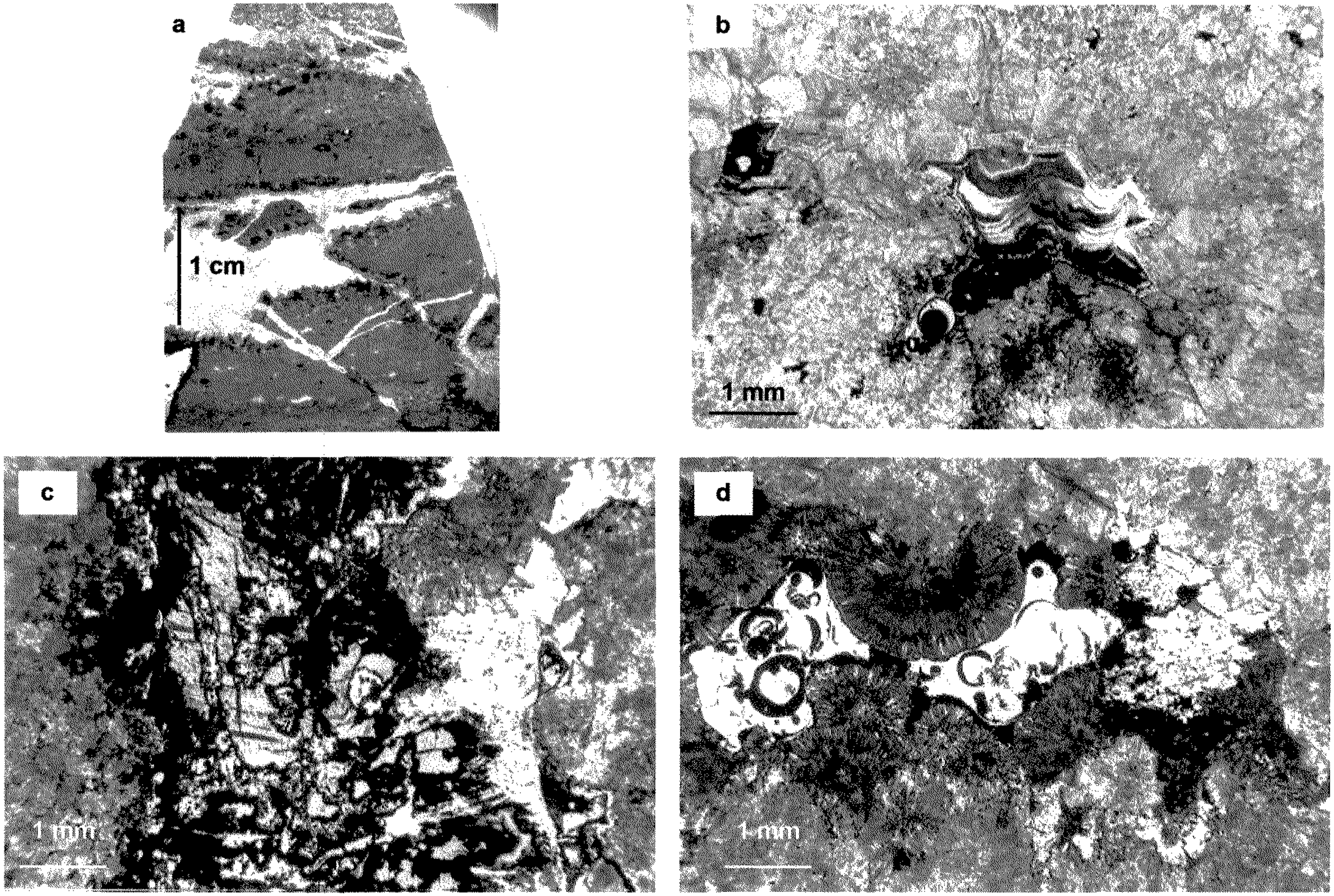


Figure 5.3. Hydrothermal dissolution features and sulphide/silicate ore minerals.

IRON OXIDES: The iron oxides consists mostly of earth-red hematite and occur in some mineralized areas cementing clasts made up of medim/coarse replacement dolostone and/or early-replaced dolomudstone, both of them associated with rhombohedral saddle dolomite. Also hematite occurs along high amplitude late stylolites as well as as solid inclusions in white saddle dolomite.

They also occur as fine particles scattered in brecciated dolostones staining them pink. Around mineralized areas the staining is pronounced, and in barren areas mostly weak and irregular. The iron oxides affect mostly lithofacies of the ooid-intraclast dolostone and dolostone members but also the lowermost unit of the dolomudstone member.

LATE-STAGE COARSE-CRYSTALLINE CALCITE (LCC): Late-stage calcite usually occurs as white to pink rhombohedral crystals commonly lining vugs or fractures, and encrusting the earlier saddle dolomite and sulfide minerals (Fig. 5.4a). Crystal size varies from millimeters to 20 centimeters. LCC postdates saddle dolomite and sulfide minerals. Small oil inclusions are often present. Under cathodoluminescence LCC is mostly dull showing a thin bright yellow to orange rim. These calcites are crosscut by late fractures.

FLUORITE: Occurs as small pockets filling small veins (centimeters long) and small vugs. It is translucent with various shades of purple color or is colorless (Fig. 5.4b). Fluorite affects LCC and could be associated with late fracturing.

SILICIFICATION: Occur as replacement and cement. The replacement is by authigenic quartz (chert); cements are chalcedony (lining cavities) and megaquartz (fills cavities). Except for small silica replacement nodules observed in the basal shallowing-upwards succession that are affected by early stylolites, silica replacement postade late dolomite replacement (Fig. 5.4c); megaquartz cement postdates sulfide minerals but precedes late calcite cement and bitumen.

Figure 5.4a-5.4d Other diagenetic features

a) Late-stage coarse-crystalline calcite (LCC) filling open fracture in dolostone. Plane light. Location: Dolomudstone member 7 (unit 7A). Imbuzeiro mine, Serra do Cantinho Hill.

b) Fluorite in small vein affecting late-stage coarse-crystalline calcite (LCC); fluorite is on the light area on the left side of the photomicrography. The host rock is replacement dolostone affected by dissolution/collapse breccia with cementation by saddle dolomite. LCC is late than saddle dolomite. Plane light. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill

c) Replacement silicification affecting grainstones; silicification occurs later than replacement dolomitization, and only the shape of the allochems is preserved. Dolomite crystals affected by silicification are still visible. Plane light. Location: Dolostone member 4. Grão Mogol Hill.

d) Bitumen filling vugs in dolostone. Dark bitumen is widespread; light areas inside vugs are of glassy to brittle bitumen, less commonly observed. Plane light. Location: Dolostone member 4, Grão Mogol Hill.

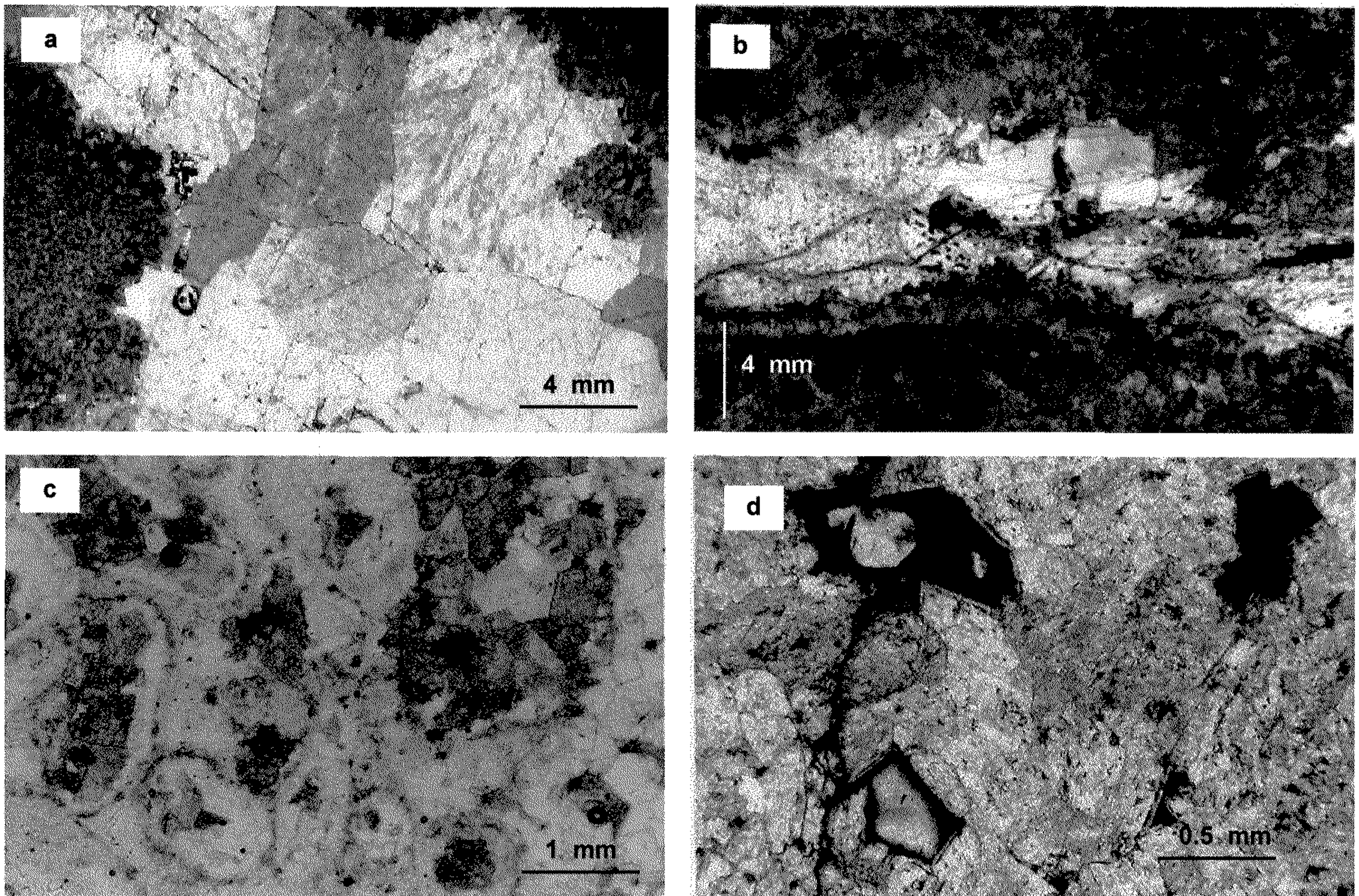


Figure 5.4. Other diagenetic features.

BITUMEN: Bitumen commonly fills vugs in the dolostone. Overlaps honey sphalerite (oil-bearing fluid inclusions) and LCC. It is the last diagenetic product. Two main types of bitumen, black and yellow ones were found (Fig. 5.4d). The black bitumen is the more common and widespread. The yellow variety is glassy to brittle bitumen (also identified in SEM) and fills vugs in dolostones. The yellow bitumen is also widespread but apparently is more common around mineralized areas.

5.4 CONCLUSIONS

Diagenetic features are interpreted to have formed in subaerial, submarine and subsurface environments.

Subaerial diagenetic features occur on the top of all the three main shallowing-upwards successions and include, in intertidal environments, minor-scale dissolution over stromatolitic reefs and dolomudstones, micritic vadose cements (pendant and meniscus), and tepees; desiccation cracks occur in supratidal zones. In the basal shallowing-upwards succession, subaerial features are not as prominent as they are in the intermediate and upper intervals of sedimentation.

In submarine or sea floor diagenetic environment the main features are mostly of intertidal zone; and there is no record of meteoric diagenesis. An acicular isopachous rim around allochems occurs in more porous units, especially in ooid-intraclast grainstones; and suggests beachrock cementation later mimetically dolomitized. This early marine cement occurs in units of the ooid-intraclast dolostone member belonging to the intermediate shallowing-upwards succession.

Subsurface diagenesis developed in shallow and intermediate burial and overprinted previous diagenetic features. In shallow burial, early dolomitization affects tidal flat lithologies and stromatolites. Early compaction with or withouth dolomite cements along microstylolites is common in argillaceous lime mudstones and in some calcirudites, and locally affects dolomudstones; besides that it defines the limits between shallow and intermediate burial. Medium to coarse dolomite replacement as well as hydrothermal dissolution, blocky and prismatic calcite cementation, dolomite cements, mineralization, and precipitation of various late-stage diagenetic products as late-stage calcite, fluorite and bitumen occur in intermediate burial.

Subsurface diagenesis has resulted in the most important diagenetic modifications in carbonate rocks of the Januária region, affecting especially sediments of the dolostone and ooid-intraclast dolostone members as well as the lowermost portion (ca. 2m) of the dolomudstone member.

CHAPTER 6

ORIGIN OF THE DOLOMITE HOSTING MINERALIZATION IN THE JANUÁRIA REGION: EVIDENCE FROM PETROGRAPHY, GEOCHEMISTRY AND FLUID INCLUSIONS

6.1 INTRODUCTION

The dolomitization of the Januária region provides a good opportunity to study the formation of ancient massive regional dolostone as well as the relationship of subsurface dolomites and mineral deposits. Understanding the origin and distribution of burial dolomites, especially saddle dolomite is of utmost importance because these dolomites host numerous sulfide, oil and gas deposits worldwide.

As summarized in Chapters 3 and 4, near shore and intertidal carbonate sediments during sedimentation and early diagenesis were influenced by evaporated seawater of high salinity and by meteoric waters during subaerial exposure. Subsurface brines modified from Neoproterozoic sea water affected carbonate sediment during subsequent burial. Dolomitization could be related to any of these fluids, or to some combination of them. Burial dolomitization is widespread, and associated with several stages of dissolution/collapse breccias and saddle dolomites cements (SD).

Little research has been carried out on the study area on the sedimentology and diagenesis of the carbonate rocks; there are no data concerning dolomitization and geochemistry. Nothing has been published concerning dolomitization and their geochemistry.

In this chapter the origin of the various 12 types of dolomites in the Januária region are investigated using petrography, cathodoluminescence, and various geochemical techniques including i) oxygen and carbon isotopes, ii) strontium isotopes, and iii) fluid inclusion measurements. The petrography, spatial distribution and geochemistry of these dolomites are discussed and their origin interpreted using all available information.

The origin of massive replacement dolomites and models of dolomitization have been controversial for a long time, despite intensive research carried out by geologists and geochemists. Dolomite has been interpreted as forming in many different environments by various fluids (Machel and Mountjoy 1986; Hardie 1987). The main dolomitization models include:

1) evaporitic marine brines (e.g. Adams and Rodhes 1960; Illing et al. 1965; Patterson and Kinsman 1982);

2) reflux dolomitization (King 1947; Adams and Rodhes 1960);

3) Coorong model (Mason 1929 *in* Morrow 1990; Von der Borch 1976; Muir et al. 1980);

4) freshwater/seawater in mixing zone (Hanshaw et al. 1971; Badiozamani 1973; Land 1973; Choquette and Steinen 1980);

5) burial dolomitization related to various subsurface fluids moved by different driving mechanisms (compaction, thermal, sedimentary and tectonic loading (squeegee), e.g. Illing 1959; Sanford 1962; Hanshaw et al. 1971; Jones 1980; Mattes and Mountjoy 1980; Aulstead and Spencer 1985; Gregg 1985; Machel and Mountjoy 1986, 1987; Morrow et al. 1986; Qing and Mountjoy 1989; Berger and Davies 1999).

New approaches to dolomitization models suggest that some regional dolomitization may be connected with sequence stratigraphy: if true, sediments deposited during transgressive and highstand system tracts could be more easily dolomitized by modified sea water (e.g. Melim et al. 2000).

The extent of dolomitization is variable in the various depositional environments due to fluid-flow parameters and variations in chemical composition of the fluids. Morrow (1982, 1990) and Land (1985) suggested that seawater was the only abundant source of Mg^{2+} for dolomitization and therefore that subsurface diluted fluids could not result in massive dolomitization due to an insufficient supply of Mg^{2+}. Based on close examination of dolomites in modern mixing zones and evaporitic environments, Machel and Mountjoy (1986) and Hardie (1987) concluded that these environments cannot produce massive dolomites and that subsurface dolomitization is probably more abundant than was previously considered. However, Melim et al

(2000) suggests that seawater trapped in the sediments and modified during burial could provide enough Mg^{2+} to produce extensive dolomitization along fault and fracture systems and other conduits.

6.2 PETROGRAPHY AND SPATIAL DISTRIBUTION OF DOLOMITES

Dolomite occurs in a wide range of crystal forms, fabrics and mosaics. Much dolomite is a replacement of pre-existing limestones and there is a wide range of replacement fabrics, but dolomite is also a cement, filling or lining voids.

In this research, replacement dolomites are dominant and were subdivided in early (penecontemporaneous) and late (burial) dolomites; dolomite cements are of great importance, especially in and around mineralized areas.

Twelve types of dolomite are found in the Januária region (Table 6.1), five of them being related to mineralized areas.

The main important dolomites are, in paragenetic sequence:

1. early, penecontemporaneous replacement dolomites: cryptocrystalline (CpCD) and microcrystalline (McCD).
2. late replacement dolomites: medium-crystalline (MCD) and coarse-crystalline (CCD).
3. dolomite cements: very coarse-crystalline (VcCD); saddle (SD), anhedral (AD) and very finely crystalline (VfCD).

The microcrystalline dolomite can be divided into two types that grade one to each other: a fine crystalline planar-s to non-planar one and another displaying sucrosic textures. The cryptocrystalline dolomite is coeval with the microcrystaline one but mainly is restricted to ooids and micritic sediments. The whole dolomudstone member consists of penecontemporaneous dolomites.

Dolomite types	Replacement		Texture		Allochems and/or ghots	Cement	Crystal			Luminescence (CL)	Spatial distribution	Observations
	early	late	preseving	not preserving			size	color/shape	extinction			
CpCD	Y		Y		Y			Pale gray	Sharp	non-luminescent	Mb 7 (6)	
McCD	Y		Y		Y		15 to50μm	cloudy	Sharp	non-luminescent	Mb 7, 5 (6)	
MCD		Y		Y	Y		250 to 368μm	cloudy	sharp	dull-red	Mb 3,4,6 (7)	
CCD		Y		Y	Y		276 to 690μm	cloudy	sharp	red dull to dull	Mb 4,6 (7)	
VcCD					very rare	Y	736 to 920μm	clear, commonly zoned	sharp	dull to non-luminescent	Mb 6 (7)	displays well defined crystal junctions
SD						y	1,25 up to 1,60mm	pink or gray (rhombohedral forms) and white (symmetrical saddle forms)	sweeping	red bright (rhombohedral forms) and dull (white SD)	Mb 6 (7)	white SD lines cavities; is later than rhombohedral SD
VfCD						y	66 to 80μm	clear	sharp	dull to non-luminescent	Mb 6 (7)	eventual lamination
DC1 **DC2**						y	180μm 50-100μm	clear	sharp	dull (DC1) orange (DC2)	Mb 7	
AD						y	500μm to up to1mm	clear	sweeping	dull	Mb 6 (7)	

Table 6.1. Summary of dolomite types described in the Sete Lagoas Formation – Januária region

The medium and coarse crystalline dolomites represent pervasive dolomite replacement of most sediments belonging to the dolomitic calcarenite member (partial replacement), the dolostone and ooid-intraclast dolostone members. Where peloids and intraclasts dominate, the dolomite replacement are of medium crystallinity; dolomite replacement affecting ooids are always coarse crystalline.

CCD is common in the Serra do Cantinho and Grão Mogol Hills.

Dolomite cements are widespread mainly in the sediments of the dolomudstone and ooid-intraclast dolostone members; and except for the very coarse-crystalline dolomite and saddle dolomite, they have no relationship with the mineralization.

6.2.1 PETROGRAPHY

Dolomitic rock textures are classified according to Sibley and Gregg (1987) and the main aspects of studied dolomites were summarized in the Table 6.1.

1. EARLY REPLACEMENT DOLOMITES

CRYPTOCRYSTALLINE DOLOMITE (CpCD)

CpCD is dark to pale gray, cryptocrystalline and non-luminescent. Dolomite mosaics are tight, have very low porosity and are texturally preserving; and characteristically occurs in muddy and ooid sediments of the dolomudstone member 7. Some intraclasts in the ooid-intraclast dolostone member 6 also consist of cryptocrystalline dolomite.

MICROCRYSTALLINE DOLOMITE (McCD)

Sedimentary structures and grains are well preserved in McCD which are generally tightly packed with interlocking crystals resulting in very low porosity. Sucrosic textures with intercrystalline porosity are minor; the shape of allochems is preserved but the internal texture is not. McCD also replaces fine grained, geopetal sediments in cavities. Silica, anhedral dolomite and bitumen cement and fill small fractures, vugs, as well as moldic and intercrystalline porosity in McCD.

Microscopically, McCD consists of dense unimodal planar-s (pl-s) to nonplanar, non-luminescence dolomite. Crystals are cloudy, unzoned, subhedral to euhedral (15 μm to 50 μm); and are clearer and coarser around porous (Fig. 6.1a). Sucrosic dolomites consist of coarser planar-s dolomite.

2. LATE REPLACEMENT DOLOMITES

MEDIUM-CRYSTALLINE DOLOMITE (MCD)

MCD replaces what are interpreted to be primary limestones. They are porous or tight depending on the presence or absence of intercrystalline porosity (Fig. 6.1b). Sedimentary structures and allochems are poorly preserved. Secondary vugs and local fractures MCD are filled mainly with late-stage coarse-crystalline calcite cement.

Microscopically MCD forms a planar-subhedral to euhedral (pl-s (e)) dense unimodal mosaic dolomite with some porous areas. Crystals are cloudy, subhedral to euhedral rhombs of dolomite (250 to 368 μm). In adjacent porous areas dolomite crystals are coarser (320 to 460 μm), euhedral, displaying planar-e(s) texture some with an outer clear rim and dark core, especially in the coarse euhedral crystals around porous zone. MCD has uniformly dull-red luminescence. MCD replaces both matrix and allochems; it is usually fabric destructive and only a few ghosts of well-rounded grains are still visible. Dolomite crystals grow over early stylolites (see Fig. 5.2d).

COARSE-CRYSTALLINE DOLOMITE (CCD)

CCD is fabric destructive with the original sedimentary and early diagenetic features mostly destroyed, but containing relics of cross-bedding and sand-sized, well-rounded allochems with concentric layers.

Figure 6.1a-6.1d Petrographic features of the replacement dolostones

a) Thin section photomicrograph of microcrystalline dolomite (McCD) with interlocking textures and irregular areas of dolomite displaying sucrosic texture; early dolomite replacement. Plane light. Location: Dolomudstone member 7 (unit 7B), Grão Mogol Hill.

b) Thin section photomicrograph of medium-crystalline dolomite. MCD forming a dense unimodal mosaic made up of planar-subhedral to euhedral dolomite (pl-s(e)), with porous areas. Remains of allochems are mostly rare; late dolomite replacement. Plane light. Location: Dolostone member 4, Grão Mogol Hill.

c) Thin section photomicrograph of coarse-crystalline dolomite. CCD composes a dense mosaic of euhedral to subhedral dolomite crystals (pl e-s); ghosts or remains of ooidal grains are still visible; late dolomite replacement. Plane light. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill.

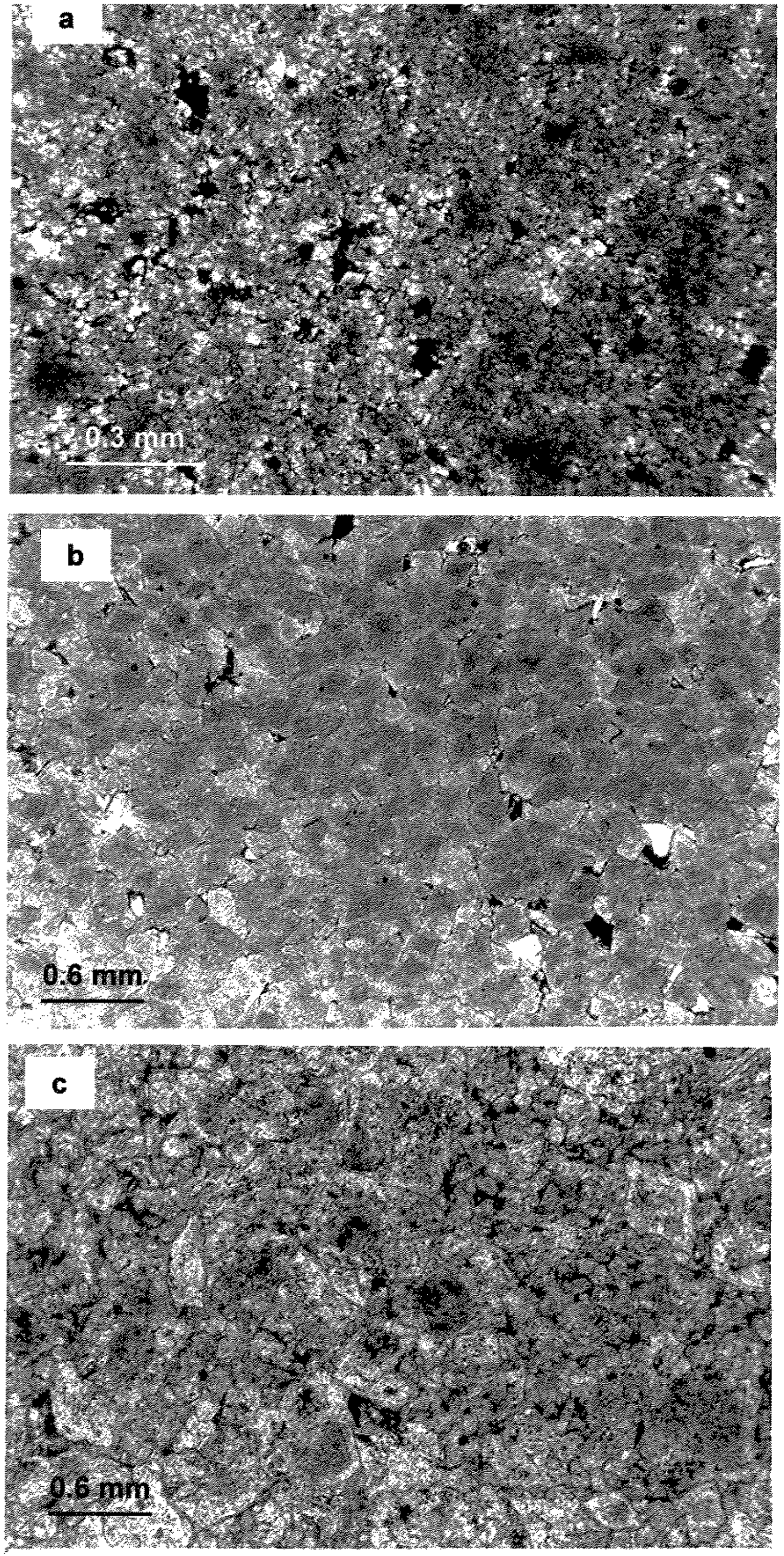


Figure 6.1. Petrography of the dolostone replacement.

CCD consists of coarse, euhedral to subhedral dolomite crystals (276 to 690 µm) making up a tight mosaic crystals (Fig. 6.1c). CCD mostly replaces mostly ooidal sediment. Around porous areas dolomite crystals are coarser and more euhedral and are zoned but in this case withouth evidence of grains.

CCD has red dull to dull luminescence with irregular medium bright orange areas that probably represent intraclasts made up of CpCD/McCD modified by late dolomite replacement.

Neomorphism may be responsible for forming local variations in CCD textures, to mostly non-planar (npl-a) with larger crystals growing over more than one ooidal grain. Dolomite crystals also become bright and clear close to late calcite cement and near mineralized areas suggesting some recrystallization by these later diagenetic fluids.

3. DOLOMITE CEMENTS

VERY COARSE-CRYSTALLINE DOLOMITE (VcCD)

VcCD is dusty to clear and the original sedimentary features, early diagenetic cements and original fabrics are mostly destroyed. Rare remains of grains (mostly well-rounded granules) are still visible. VcCD contains a large variety of vugs and fractures, ranging in size from mm to cm; and forms irregular patches in sharp and irregular contact with MCD and CCD, being younger than these two dolomites.

VcCD may comprises a dolomite mosaic of coarse to very coarse euhedral to subhedral, dull to non-luminescent dolomite crystals (736µ m to 920 µm) but around vugs or porous areas crystals are coarser (1,15 mm) and show well-defined crystal junctions; zoning is common and crystal exctintion is sharp (Fig. 6.2a). It is considered as representing dolomite cement that overprinted earlier replacement dolomites.

SADDLE DOLOMITE (SD)

In hand specimen saddle dolomite is pink or white in color. SD usually consists of very-coarse dolomite crystals (1,25 up to 1,60 mm). Crystal shape varies from rhombohedral, with slightly curved crystal faces (Fig. 6.2b), to symmetrical saddle forms (up to 2mm) through increasingly curved-face (Figure 6.2c). Usually, symmetrical saddle forms have a distinctive white colour and line pore-spaces frequently in rhombohedral saddle dolomites. SD occurs mainly as cement in vugs and fracture in CCD and VcCD postdating these two dolomite types. Fracturing and dissolution are recurrent, affecting especially areas of rhombohedral form of SD which have fractured crystals and vugs filled of willemite needles.

SD is usually associated with sulfide minerals. Rhombohedral saddle dolomite commonly predates mineralization. Saddle dolomite also overlaps with mineralization because white symmetrical forms under SEM show numerous solid inclusions of iron oxide (possibly hematite) lacking in sulfide and silicate ore minerals.

Rhombohedral SD crystals have a diagnostic sweeping extinction pattern (Fig. 6.2c) that luminesce red-bright with minor zonation (Fig. 6.3a), but far from mineralized areas are dull. The white symmetrical SD has dull or lack luminescence (Fig. 6.3b). Near mineralized areas rombohedral SD are zinc-rich and iron-poor.

VERY FINELY CRYSTALLINE DOLOMITE (VfCD)

VfCD constitutes very irregular pockets or layers in the dolomitized/brecciated interval (Fig. 6.4a). In barren areas vugs are small (mm to cm) but in mineralized areas cavitied filled of VfCD are bigger (dm to meters). VfCD is later than VcCD and rhombohedral SD being affected by later diagenetic events as high-amplitude stylolites, late calcite, fluorite and bitumem.

VfCD forms a planar subhedral to non-planar (pl-s to npl-a), dull to non-luminescence, dense, tight unimodal mosaic dolomite. Dolomite crystals are clear, mostly subhedral to anhedral (66 to 80μm); euhedral as well as rounded crystals are not uncommon (Fig. 6.4b). Remains of corroded and/or broken peaces of very-coarse dolomite or saddle crystals are common inside pockets of VfCD (Fig. 6.4c). No ghosts of allochems are observed with VfCD. VfCD exhibit laminations and sometimes normal grading. VfCD occurs in the whole study area but becomes prominent around mineral deposit as at Serra do Cantinho (Imbuzeiro mine and Serrotinho) and Serra da Umburana Hills as infilling cavities of different sizes. It cements all kinds of breccia fragments made up of McCD, MCD, CCD, VcCD and SD.

Figure 6.2a-6.2c Petrographic features of dolomite cements

a) Thin section photomicrograph of very coarse-crystalline dolomite. VcCD crystals are dusty to clear, and remains of allochems are absent. Crystals are frequently zoned with buffed areas possibly resulting from neomorphism. Plane light. Ooid-intraclast dolostone member 6. Grão Mogol Hill.

b) Thin section photomicrograph of rhombohedral saddle dolomite crystals (SD) with curved crystal boundary. Plane light. Location: Dolomudstone member 7 (unit 7A), Serra do Cantinho Hill.

c) Thin section photomicrograph of white saddle dolomite crystals displaying saddle forms. White saddle dolomite is later than rhombohedral forms. Sweeping extinction can be observed. Crossed nicols. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill.

d) Thin section photomicrograph of anhedral dolomite (AD). Anhedral dolomite crystals range from 500μm to up to 1mm, fills cavities and under crossed nicols exhibit undulatory extinction. Crossed nicols. Location: Dolomudstone member 7 (unit 7B), Grão Mogol Hill.

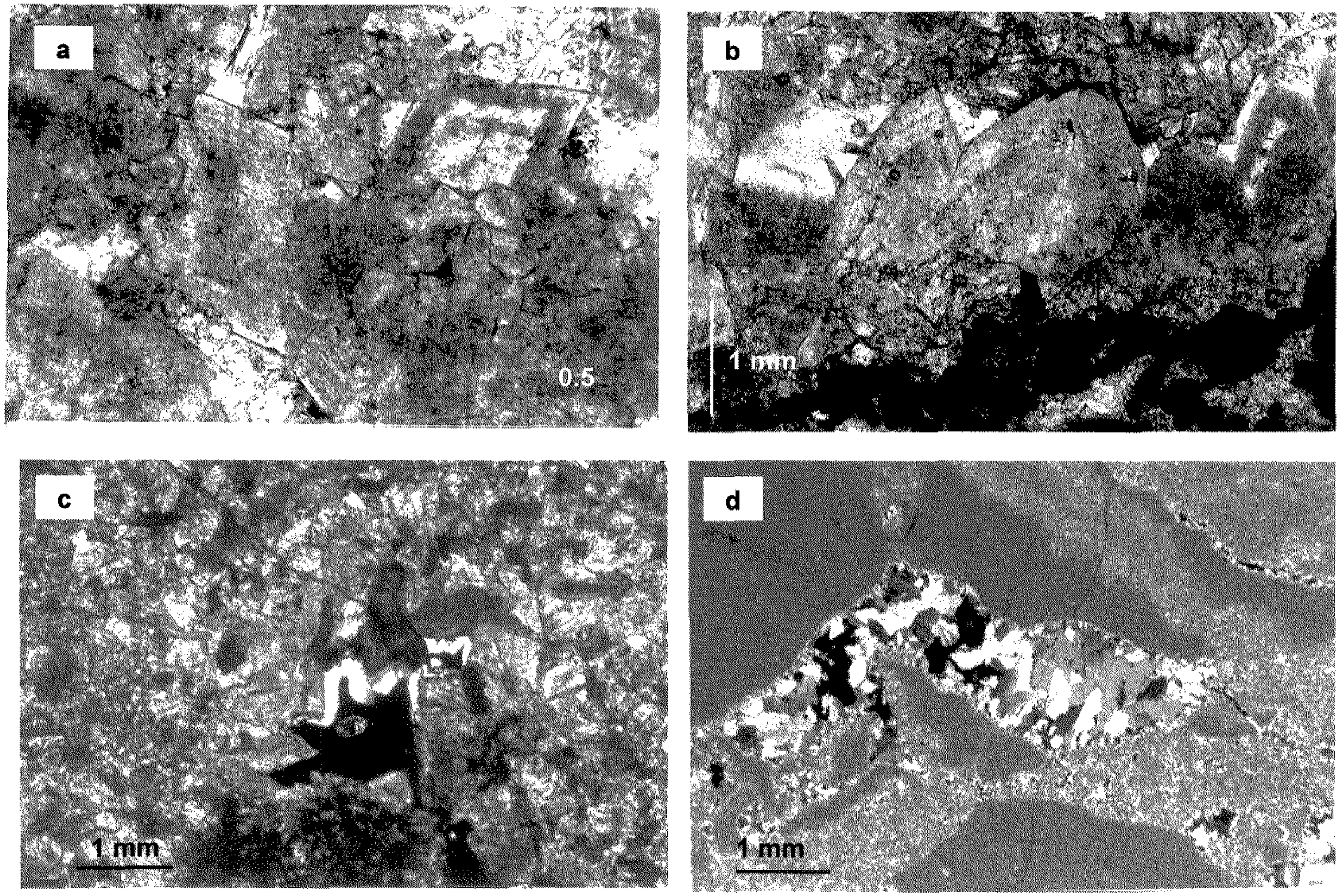


Figure 6.2. Petrographic features of dolomite cements.

Figure 6.3a and 6.3b Dolomite cements (saddle forms) under cathodoluminescence light.

a) Thin section photomicrograph of rhombohedral saddle dolomite under cathodoluminescence light (CL). Saddle dolomite is red-bright luminescent with weak zonation. Location: Dolomudstone member 7 (unit 7A), Serra do Cantinho Hill.

b) Thin section photomicrograph of white saddle dolomite, with characteristic symmetrical saddle forms, under cathodoluminescence light. White saddle dolomite is dull under CL. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill.

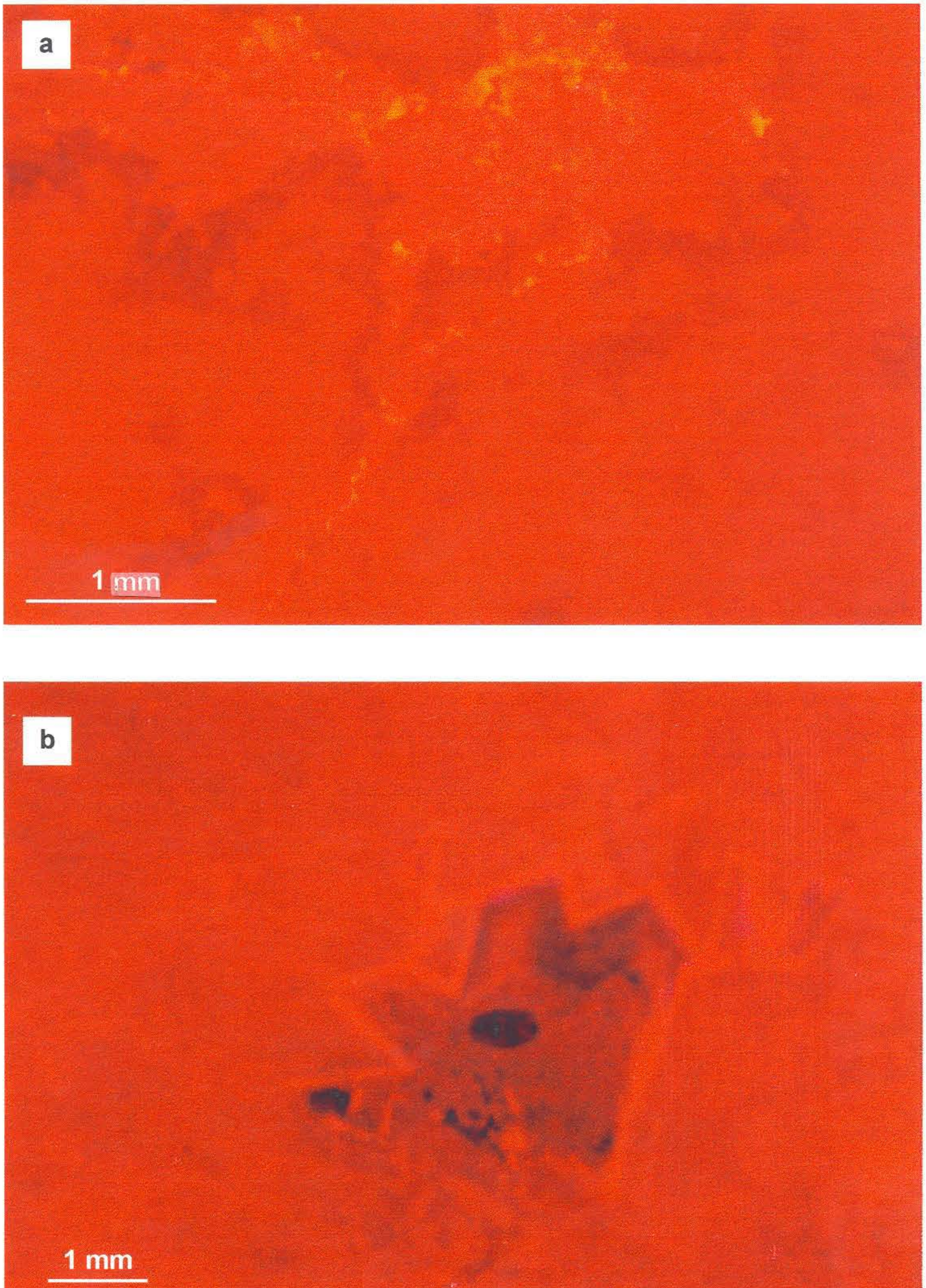


Figure 6.3. Dolomite cements (saddle forms) under cathodoluminescence light.

VfCD is interpreted to be an internal sediment resulting from large-scale dissolution that affected all prior dolomites before, or in the initial stage, of the ore mineral emplacement. Although detrital grains of ore mineral were not found associated with VfCD, it is intimately related to ore mineral locally hosting sulfide minerals.

Closely related to VfCD, threre are very fine euhedral dolomite rhombs, scattered or composing a loose mosaic cemented by poikilotopic calcite (Fig. 6.3d). These rhombs are completely translucent or have dark cores; crystals are bright orange and those with dark cores are dull. They are commonly observed on the top of cavities and sometimes seem to nucleate over light colored mud. These very fine euhedral dolomite rhombs are interpreted as a late cement, later than VfCD.

MINOR DOLOMITE CEMENTS (DC)

These cements were observed in barren areas (see Fig. 5.2a) and two main types, named DC1 and DC2, described.

DC1: this dolomite cement occur as rim (180μm) lining cavities and are dull, non-luminescent; cavities are later filled with not luminescent blocky sparry calcite. The whole ensemble is affected by late, almost vertical high amplitude stylolite and later affected by fine fracturing. It is commonly observed in dolomudstones, especialy those of the unit 7A.

DC2: is of very fine to fine crystallinity (55 to 100μm), and bright yellow luminescent; lines or fills small cavities resulting from dissolution non-fabric selective in dolomudstones belonging to the unit 7A. Some vugs seem resulting from dissolution inside a network of stylolites. It was not possible to define the relationship of this dolomite cement with the coarse dolomite cement (DC1) and blocky sparry calcite.

DC cements are later than early dolomitization but there is no crosscut relationship with late replacement dolomites or other dolomite cements; certainly they are earlier than anhedral dolomite; they are not showed in the Table 5.1.

Figure 6.4a- 6.4d Petrographic features of very finely crystalline dolomite (VfCD)

a) Photomicrograph of very finely crystalline dolomite filling cavities and cementing clasts in dissolution/collapse breccia. Plane light. Location: Dolomudstone member 7 (unit 7A), Serra da Umburana Hill.

b) Detail of the photomicrograph a, showing a planar subhedral to non-planar unimodal mosaic; rounded crystals can be observed (arrow). Plane light. Location: Dolomudstone member 7 (unit 7A), Serra da Umburana Hill.

c) Thin section photomicrograph showing very-coarse dolomite rhombs (VcCD) affected by very finely crystalline dolomite (VfCD). Crossed nicols. Location: Ooid-intraclast dolostone member 6, Serrotinho.

d) Thin section photomicrograph showing very fine euhedral dolomite crystals that occur frequently associated with VfCD. Very fine euhedral dolomite rhombs are cemented by poikilotopic calcite. Plane light. Location: Dolostone member 7 (unit 7A), Grão Mogol Hill.

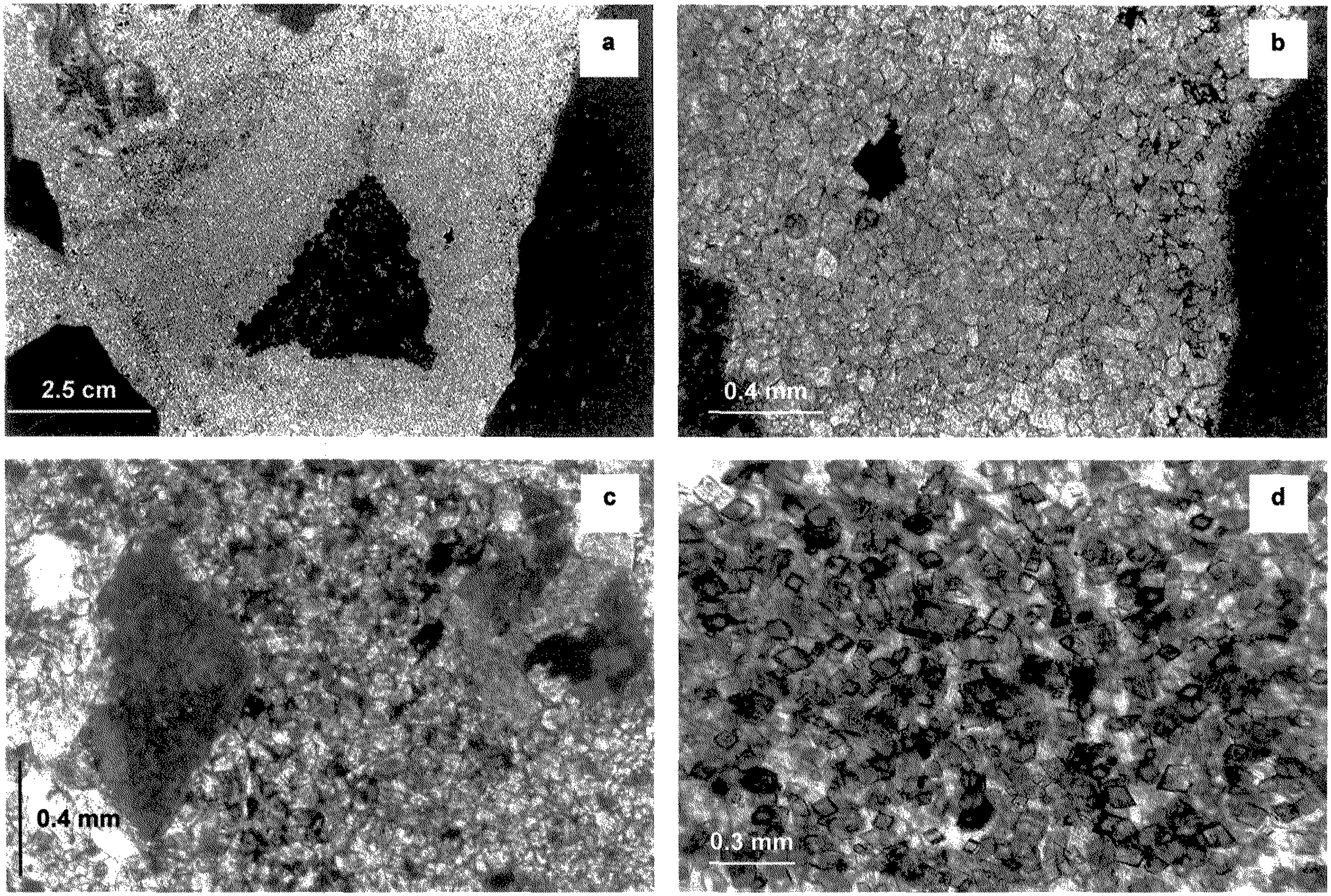


Figure 6.4. Petrographic features of very finely crystalline dolomite.

ANHEDRAL DOLOMITE (AD)

Anhedral dolomite consists of coarse to very coarse crystalline (500µm to up to 1mm), nonplanar-anhedral (npl-a) dolomite cement (baroque or white sparry dolomite). Crystals are composite and serrated crystal boundaries, and they exhibit a characteristic sweeping extinction (Fig. 6.2d).

AD is a cement that fills vugs, usually associated with bitumem. AD cementation seems to occur prior to bitumen emplacement.

6.2.2 SPATIAL DISTRIBUTION OF DOLOMITES

McCD is found in the stromatolitic buildups and fine sediments of stromatolite dolostone member 5; it also comprises up to 95% of the dolomudstone member 7. Finely laminated or muddy intraclasts found in the ooid-intraclast dolostone member also display this texture. McCD fills cavities related to subaerial exposure in the stromatolitic barrier or in tidal flats. Dolostone of sucrosic texture commonly replaces finely laminated mudstones probably of coarse silt-size and wackestones to packstones made up of allochems similar to microphytolites.

Cryptocrystalline dolomite (CpCD) is minor and mostly replaces ooids and micritic sediments of the dolomudstone member 7.

MCD is observed affecting lithologies from the uppermost dolomitic calcarenite member 3 to the lower part of the ooid-intraclast dolostone member 4, especially at Grão Mogol Hill.

CCD characteristically overprints ooidal sediment of the dolostone and ooid-intraclast dolostone members (4 and 6). CCD is more commonly observed in the Serra do Cantinho Hill. MCD and CCD are basically found at the same stratigraphic position and can be gradational one to another. Neomorphism of MCD and CCD promotes changes in the described pattern (see Chapter 5).

VcCD mostly affects areas of coarse to very-coarse intraclast to pseudo-intraclasts grainstones, but also ooidal grainstones belonging to the ooid-intraclast dolostone member 6.

VcCD is frequently observed in areas with well-developed dissolution/collapse breccias, in barren and mineralized areas.

SD is commonly found in the ooid-intraclast dolostone member 6, in the lowermost part of the dolomudstone member 7, and exceptionally in the uppermost portion of the dolostone member 4. It is abundant in and around mineral deposits; far from mineralized areas SD becomes scarce.

The rhombohedral saddle dolomite commonly fills and lines pore spaces in areas of dissolution/collapse breccias and in open fractures in dolomudstones. Locally can develop a texture similar to the zebra dolostone.

Symmetrical saddle form is later than rhombohedral one and is commonly found in cavities of the ooid-intraclast dolostone member 6.

VfCD is widespread, always present in areas of dissolution/collapse breccia and late than brecciation cemented by rhombohedral SD. It fills irregular cavities in the dolostone frequently in association with intraclasts made up of MCD, CCD, VcCD, SD and angular intraclasts of the dolomudstone member 7 (unit 7A), all of them representing wall rock intraclasts. VfCD may display normal grading, and usually is associated with dissolution/collapse breccia in and around mineralized areas. Cavities filled with VfCD are small in barren areas and bigger in mineralized areas.

Dolomite cements (DC) of different generations and crystallinity are widespread lining or filling cavities in the dolomudstone member, especially in barren areas.

AD is very minor and fills vugs in the McCD (dolomudstone member 7) and CCD dolomites (ooid-intraclast dolostone member 6).

6.3 STABLE ISOTOPES

O and C isotopes provide information about the depositional environment and the rocks diagenetic history.

$\delta^{18}O$ values are affected mainly by temperature and evaporation with the heaviest values occurring in marine waters, and the lightest values due to higher temperature brines. $\delta^{13}C$ values are influenced by the type of C available with heavier values indicating marine conditions and lighter values resulting from rainwater or fluids that have passed trough soil horizons.

Together O and C isotopes help to distinguish between several different modern and diagenetic settings.

The $\delta^{18}O$ values of dolomites are controlled by four factors; the $\delta^{18}O$ value of dolomitizing fluids, the $\delta^{18}O$ values of limestone precursor, the water/rock ratio, and the temperature, assuming bulk solution equilibrium (Land 1980; 1983). Although the dolomite/water fractionation is poorly constrained, it is generally accepted that dolomite precipitated in isotopic equilibrium with seawater should be at about 2-4‰ heavier than the coexisting calcite (Land 1980, McKenzie 1984; Tucker and Wright 1990). During later diagenesis, the original $\delta^{18}O$ may be modified and/or re-set.

The carbon isotopic composition of the dolomite reflects the ratio of inorganic carbon derived from pre-existing limestones and dolomite to organic carbon derived from the microbial and thermal breakdown of organic matter (Allan and Wiggins 1993). With increasing depths of burial and time the chances of diagenetic changes increase, and as fluids contain much less carbon than oxigen, $\delta^{13}C$ values are though to be less affected by diagenesis than $\delta^{18}O$ values (Hoefs 1997).

In this study, four types of dolomites (McCD, MCD/CCD, VcCD/SD and VfCD), fine crystalline calcite mudstones and late calcite cements were sampled and analized for oxygen and carbon isotopes.

It is important to estimate the isotopic signature of the Neoproterozoic seawater of the Sete Lagoas Formation as a bench mark for comparison in order to determine the degree of diagenetic modification. However available geochemical data are insufficient to refine the data base concerning the isotopic signature of Neoproterozoic seawater. Because of this, values of $\delta^{18}O$ will be discussed using PBD as a standard instead of SMOW, avoiding in this way direct comparison between Neoproterozoic (Sete Lagoas Formation) and modern seawater.

Oxigen and carbon isotopes were measured on limestone, calcisiltites and calcirudites from the basal argilllaceous lime mudstone and calcirudite members. Eight samples of limestone have values $\delta^{18}O$ values (PDB) ranging from –6.11 to –6.56‰ (mean = -6.39) and $\delta^{13}C$ ranging from 0.26 to 0.58‰ (mean = 0.42‰) (Fig. 6.5). These heavy $\delta^{18}O$ values may represent the inferred composition of seawater or slighly modified seawater during deposition of the Sete Lagoas Formation.

Four types of dolomites were analysed, microcrystalline (McCD), medium to coarse crystalline dolomite (MCD/CCD), very coarse crystalline plus rhombohedral saddle dolomite (VcCD/SD) and very finely crystalline dolomite (VfCD).

Microcrystalline dolomites (McCD) have $\delta^{18}O$ values of –4.63 to –5.42‰ (mean = -4.95‰) that are heavier than the hypothetic seawater values. Values of $\delta^{13}C$ in McCD are highly variable, from 0.76 to 2.85‰.

Medium and coarse-crystalline dolomite (MCD, CCD) contain $\delta^{18}O$ values ranging between –6.94 to –7.66‰ (mean = -7.42‰) and $\delta^{13}C$ values of 2.32 to 2.82‰ (mean = 2.57‰).

As VcCD and SD rarely make up large masses, and difficult to sample with confidence each of the diagenetic phases. For this reason, using thin sections as a guide, three samples of dolostones showing a predominance of rhombohedral saddle dolomite and VcCD over CCD/MCD were sampled. This procedure allows us, though indirectly, to identify changes in the values of $\delta^{18}O$ and $\delta^{13}C$ based on the relative amounts of the VcCD and saddle cement compared to MCD/CCD.

Samples with significants amounts of VcCD and saddle dolomite cement contain a range of lighter $\delta^{18}O$ values compared with MCD and CCD dolomites. $\delta^{18}O$ values varies from –8.40 to –9.62‰ (mean = -9.09‰). $\delta^{13}C$ values are similar to replacement dolostones with average of 2.40‰. One sample of rhombohedral saddle dolomite adjacent to mineralized area yields $\delta^{18}O$ value of –8.02‰ and $\delta^{13}C$ value of 2.31‰

Two samples of very finely crystalline dolomite (VfCD) have $\delta^{18}O$ values heavier than the hypothetic seawater: -4.48‰ and –5.10‰ PDB but are within the 2 to 3 mil range of $\delta^{18}O$ values calculated for dolomites that would precipitate from Neoproterozoic seawater. The $\delta^{13}C$ values are of 3.39‰ and 3.0‰ PDB.

Two samples of late-stage coarse-crystalline calcite from mineralized area shows $\delta^{18}O$ values of –13.40‰ and $\delta^{13}C$ values of 1.27‰ The analytical results for Carbon and Oxigen isotopes are show in the Figure 6.5, a cross plot diagram of $\delta^{18}O$ and $\delta^{13}C$.

6.3.1 DISCUSSION

Values of $\delta^{18}O$ ranging from –6.11 to –6.56‰ (mean= -6.39) obtained in this research from basal limestones, are the heaviest values and are considered to be the best approximation of seawater composition during deposition of the Sete Lagoas Formation. This assumption is supported by similar values found in limestones of similar stratigraphic position in the southwestern part of the basin (Arcos region – see Figure 2.1). In Arcos area, 18 limestone samples from the basal limestone level have $\delta^{18}O$ values ranging from –6.04 to –7.85‰ (mean= -6.49); based on samples from Nobre-Lopes (1995, M. Sc. Research; analytical results are available in Chang, 1997).

$\delta^{13}C$ values obtained from limestones of the Januária region are also consistent when compared with the same stratigraphic level in the Arcos region. In Mina da Bocaina values range from 0.47 to 1.28‰ (mean=0.99‰), the slightly higher values being related to a microbial buildup. Microbial limestones (6 samples) show $\delta^{13}C$ values ranging from 1.20 to 1.33‰ (mean 1.26‰) while $\delta^{13}C$ of 0.86‰ are mean values found in calcisiltites.

Limestones have mean $\delta^{18}O$ values of –6.39‰ and $\delta^{13}C$ values characteristically around zero, with mean = 0.42‰. The uppermost carbonate rocks are partially to totally dolomitized, thus values of $\delta^{18}O$ are unsuitable for estimating values of $\delta^{18}O$ of Neoproterozoic seawater.

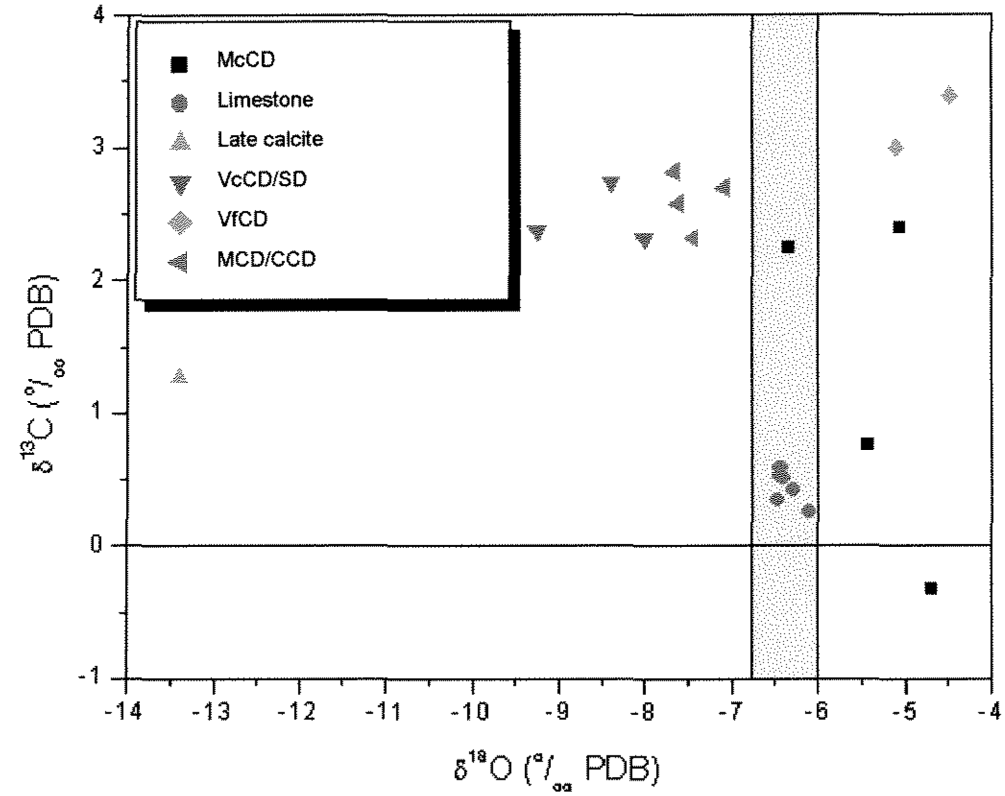


Figure 6.5. Cross plot of $\delta^{18}O$ and $\delta^{13}C$ for limestones, microcrystalline dolomite (McCD), medium to coarse crystalline dolomite (MCD/CCD), very coarse crystalline dolomite and rhombohedral saddle dolomite (VcCD/SD), very finely crystalline dolomite (VfCD) and late calcite. (*The gray area represents the hypothetic seawater composition during deposition of the Sete Lagoas Formation*).

Microcrystalline dolomite (McCD): displays $\delta^{18}O$ values with mean = -4.95‰ which is almost 2‰ heavier than the basal limestones suggesting that the dolomitization fluids could be slightly modified seawater. Microcrystalline dolomite is mainly observed in dolomudstones of peritidal environments where water salinity commonly is higher than normal seawater because of evaporation. To reinforce this interpretation, McCD is early diagenetic and texturally preserving.

Medium and coarse crystalline dolomite (MCD and CCD): The heaviest $\delta^{18}O$ value is -6.94‰. Other $\delta^{18}O$ values fall between –7.45 to –7.66‰

If dolomitizing fluids that precipitated MCD and CCD were seawater-related, the inicial $\delta^{18}O$ values would have been around –4,4 to –2,3‰ compared with the estimated Neoproterozoic seawater or even heavier (Land 1980). However the $\delta^{18}O$ values are lighter than expected if dolomitization was related to Neoproterozoic seawater.

The main processes responsible for driving the oxigen isotopic composition of diagenetic carbonate to more negative values are: elevated temperature and presence of meteoric waters. As dolomite rarely forms from meteoric waters, significant depletion in $\delta^{18}O$ in dolomite are usually taken to indicate modification at elevated temperature, mostly under burial conditions (Allan and Wiggins 1993; Qing and Mountjoy 1994a; Mountjoy et al. 1999).

The depleted δ^{18} O values also could be related to neomorphic process afecting previous replacement dolomite during later diagenesis; as dolomites usually achieve in subsurface, the initial chemical and petrographic properties are affected in various degrees (Land 1985)

The option relating $\delta^{18}O$ values to the influence of meteoric water seems unlikely because (see Chapter 4 for details) of the lack of vadose textures and meteoric cements in units afected by MCD/CCD suggests no influence of meteoric waters. Also, in vertical profiles, positive $\delta^{13}C$ values of MCD and CCD have a consistent narrow range throughout the whole sequence suggesting that the influence of meteoric water was negligible.

Thus, depleted $\delta^{18}O$ values in MCD and CCD suggest late diagenetic neomorphism over previous dolomite during burial, at elevated temperature.

Very coarse-crystalline dolomite and saddle dolomite (VcCD and SD) in MCD/CCD:

VcCD and SD are discussed together because they are closely associated with each other and have similar $\delta^{18}O$ and $\delta^{13}C$ values; the MCD and CCD influence was discussed earlier. It is important to recognize that:

i) CCD/MCD with high content of VcCD and SD are the most depleted in $\delta^{18}O$ as compared to any other dolomite diagenetic phase, including MCD and CCD;

ii) Where VcCD and SD are dominant, $\delta^{18}O$ and $\delta^{13}C$ values are similar, suggesting that both formed from dolomitizing fluids with similar $\delta^{18}O$ values.

Elevated temperature and meteoric effect make oxygen isotopic compositions more negative. However, as already discussed, because dolomite rarely forms from meteoric water, and saddle forms are related to high temperature, signifiant $\delta^{18}O$ depletion in dolomite is usually taken to indicate precipitation at elevated temperature during burial (Allan and Wiggins 1993; Qing and Mountjoy 1994a,b; Mountjoy et al. 1999). Because of this, the gradual depletion of $\delta^{18}O$ of VcCD and SD is attributed to the elevated temperatures during burial. Fluid inclusion data reinforce this interpretation.

Very finely crystalline dolomite (VfCD): δ^{18} O values are heavier than the hypothetical seawater: -4.48‰ and –5.10‰ but within the range of calculated $\delta^{18}O$ values for dolomites that would precipitate from the estimated Neoproterozoic seawater. The $\delta^{13}C$ values are of 3.39‰ and 3.0‰.

Heavy $\delta^{18}O$ values are usually considered as resulting from high salinity formation brines, sometimes associated with base metal mineralizations, or by infiltration of evaporated surface waters.

Considering that:

1. VfCD is frequent near and in mineralized areas; also VfCD is closely related to sulfide ore mineral
2. VfCD occurs as pockets containing corroded and/or broken peaces of SD

3. VfCD pockets are found in the ooid-intraclast dolostone member and in the lowermost units of the dolomudstone member, but lacks in the uppermost units where evidences of intertidal to supratidal environments could explain the heavier $\delta^{18}O$ values
4. VfCD lacks features suggesting subaerial or submarine diagenesis
5. salinity of mineralizing fluids in MVT and Irish-type mineral deposits is usually high (10 to 30% weight) and $\delta^{18}O$ values higher than related seawater

VfCD is interpreted as resulting from high salinity brines related to mineralizing fluids, instead formed from modified Neoproterozoic seawater.

Late-stage coarse-crystalline calcite (LCC): Decrease of $\delta^{18}O$ values related to seawater and dolomites in mineralized areas suggest precipitation of LCC from warm diagenetic fluids of low salinity (with the addition of meteoric waters?). The slightly depleted values compared with other dolomites could indicate input of light carbon, possibly from alteration of organic matter during hydrocarbon generation (oil inclusions). The observed bubble contraction during freezing runs in LCC fluid inclusions indicate low-salinity (Roedder 1984); homogeneization temperatures obtained in the same fluid inclusions of LCC confirm the presence of warm fluids (see section 5.5).

6.4 RADIOGENIC ISOTOPES

The $^{87}Sr/^{86}Sr$ ratio of seawater is controlled by mixing of strontium from three main sources: sialic rocks of continental crust, volcanic rocks and marine carbonate rocks, and also hydrothermal circulation along mid-ocean ridges. Changing proportions of Sr derived from these different sources define the $^{87}Sr/^{86}Sr$ ratio in the ocean at any given time (Faure 1986).

Evidence from Phanerozoic rocks demonstrate that the $^{87}Sr/^{86}Sr$ ratio in seawater has varied systematically during geological time but has apparently been constant in the open ocean at any given point in time (Burke *et al.* 1982).

Isotopic fractioning of Sr during carbonate precipitation is negligible. The Sr isotopic composition of marine carbonate minerals is assumed to be representative of seawater at the time of the deposition (Veizer 1983).

These assumptions allow the isotopic composition of the oceans in a specific geological interval to be determined. These values are then used as a reference for diagenetic changes in carbonate sediments as well as age constraints.

Isotopic chemostratigraphy of stratigraphic sections show secular variations in isotopic seawater over time, but the Precambrian time is still constrained compared to the Phanerozoic. However the Sr isotopic composition of Neoproterozoic carbonates defines a curve of great geochemical and stratigraphic interest (Knoll and Walter 1992; Shields 1999).

The $^{87}Sr/^{86}Sr$ ratio of seawater during deposition of the Sete Lagoas Formation is estimated to be between 0.7076 and 0.7079 based on micritic limestones at the base of the section. This estimate is used below to determine post-depositional diagenetic changes in radiogenic Sr. Figure 6.6 show Sr results.

6.4.1 DISCUSSION

The $^{87}Sr/^{86}Sr$ ratio of the Sete Lagoas Formation is defined according to analytical data from basal limestones of members 1 and 2, and estimated to be between 0.7076 and 0.7079; is considered as representing the seawater at the time of Sete Lagoas Formation deposition.

Microcrystalline dolomite (McCD): of subtidal origin is slightly more radiogenic than the range of the estimate $^{87}Sr/^{86}Sr$ ratios of limestones from the Sete Lagoas Formation and presumed to represent Neoproterozoic seawater. If precipitated or related to evaporated seawater, the Sr composition of these dolomite should be similar to seawater values. Thus, the slightly higher $^{87}Sr/^{86}Sr$ ratios would suggest that the isotopic signatures were modified by later diagenetic fluids.

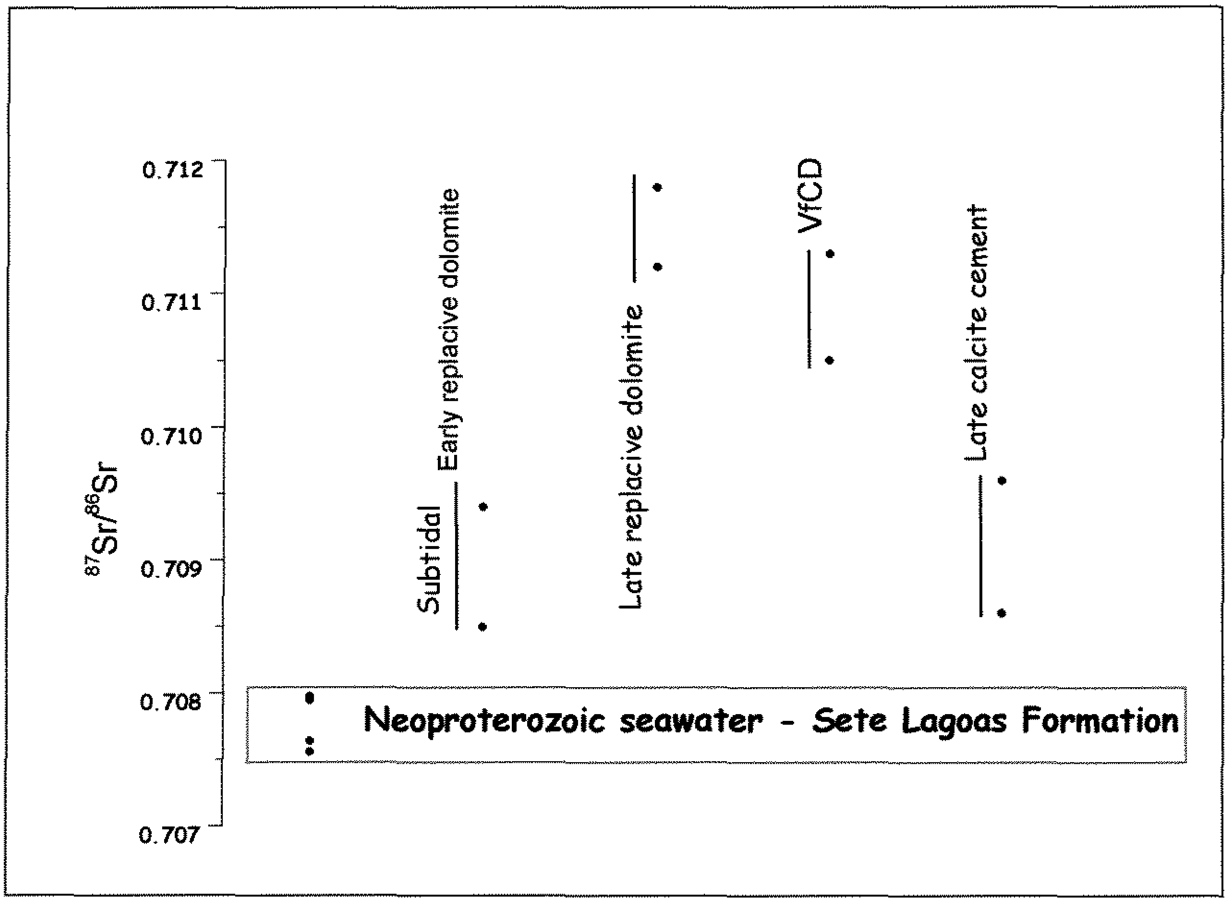


Figure 6.6. $^{87}Sr/^{86}Sr$ ratios of dolomites and late calcite. The best estimated $^{87}Sr/^{86}Sr$ ratio of Neoproterozoic seawater ranges from 0.7056 to 0.70798 according to this research.

Medium and coarse crystalline dolomite (MCD/CCD) and MCD/CCD with subordinate very-coarse crystalline dolomite (VcCD): have ratios more radiogenic than the suggested ratios for seawater composition. These data suggest that probably dolomitizing brines were allochtonous and interacted with terrigenous sediment or basement rocks before entering the carbonate units (Allan and Wiggins 1993).

Very finely crystalline dolomite (VfCD): The Sr ratios are more radiogenic than the Sete Lagoas Formation seawater. Sr ratios of VfCD are similar to or less radiogenic than those of CCD/MCD with or withouth VcCD. VfCD are interpreted as resulting from partial dissolution of the previous replacement dolomites and cements by warm brines.

Late-stage coarse-crystalline calcite (LCC): The Sr ratios (0.7096 and 0.7086) are slightly more radiogenic than the inferred Neoproterozoic seawater (Sete Lagoas Formation). LCC is the latest diagenetic phase related to mineralization and Sr isotopic composition was possibly related to warm low-salinity fluids (see fluid inclusions in LCC) with contamination of Sr-rich allochthonous brines of low-salinity (meteoric waters?).

6.5 FLUID INCLUSIONS

Two phases (aqueous liquid-vapour) were analized from 6 samples, two each of fluorite, late calcite, and saddle dolomite from the Serra do Cantinho Hill.

Honey colored sphalerite shows numerous fluid inclusion populations, mostly are two-phase (liquid/vapour) but oil inclusions are also present. Fluid inclusions in sphalerite were not analysed.

Fluid inclusion analysis allows one to determine the minimum entrapment temperature of different diagenetic fluids. A total of 60 fluid inclusions were analysed, most of them from LCC and fluorite; with few results from saddle dolomite. Three measurements were done for each fluid inclusion in order to improve data precision.

Primary inclusions form at the time of crystal growth, and are commonly concentrated in planes parallel to growth zones. Secondary inclusions are entrapped at any time after crystal growth was completed. They generally occur along healed fractures that cut crystal boundaries. Pseudosecondary inclusions are doubtful in that they can be primary or secondary in origin. The fluid inclusions measured in this study are mostly pseudosecondary or secondary because most of them are in line and do not follow zoning of crystal growth. Few fluid inclusions can be considered primary.

Homogeneization temperatures (Th) are measured during progressive heating runs. This is the temperature at which two phases (aqueous liquid-vapour in our study) initially contained in an inclusion homogenize to a single phase. Homogeneization temperatures provide an estimate of the minimum temperature at which the fluid was trapped. Usually the homogeneization temperatures are corrected for burial pressures but in this research this has not been done because of the few data available.

The initial or eutectic melting temperatures (Te) and final melting temperatures (Tm) are measured during freezing runs. Initial melting temperatures provide informations about the composition (salinity) of the fluids contained in the inclusions. The final melting temperature is the temperature at which the last ice or salt-hydrate melts.

Freezing runs to determine Te and Tm, and consequently salinity of the fluids, were made on LCC and fluorite but not saddle dolomite. For this reason, data related to salinity of the fluids are only mentioned but not discussed.

LATE –STAGE COARSE-CRYSTALLINE CALCITE (LCC)

Fluid inclusion data of LCC were obtained from the Serra do Cantinho Hill. LCC contains two-phase (LV) aqueous inclusions and monophasic dark fluid inclusion. Only two-phase aqueous fluid inclusions were analyzed. Two main populations, A and B, were identified; both are probably secondary. Isolated and rare bigger two-phase fluid inclusions were also studied. LCC crystals frequently exhibit dark inclusions.

A population: fluid inclusions occur scattered with shapes ranging from negative crystals to globular, with smooth surface; size is ~ 40μm and the ratio of liquid to vapor is of ~15%. Fluid inclusions are considered to be secondary or pseudosecondary because they are scattered or poorly aligned; with no relationship to zoning in the crystals. LCC has dull luminescence.

The eutectic temperature (Te) varies between –43 and -54^0C but temperatures from -50 to -54^0C are more common. Comparing these eutectic temperatures with data from Crawford (1981), the fluid inclusions belong to the system H_2O-NaCl-$CaCl_2$ but other divalent cations such as Mg^{2+} should be present (Goldstein and Reynolds 1994) to explain the variations in the -52.2^0C in the Te of this system. During freezing bubbles contracted indicating that inclusions are H_2O-rich and have low salinity (Roedder 1984).

Homogeneization temperatures of A population range from 124.5 to 132.5^0C and bubbles remain stationary throughout the heating runs.

B population: fluid inclusions occur in line, are secondary and globular with smooth surface, size varies from 20 to 25µm and the ratio of liquid to vapour is ~10%. Characteristically the bubbles in this population are in constant motion within the vacuole.

Homogeneization temperatures range from 108 to 114.8^0C.

Isolated two-phase fluid inclusions: are globulous or show negative crystal shape with smooth surface; sizes are around 60µm. Homogeneization temperatures (Th) are of 148 to 149^0C and 188.6 to 189.5^0C. These fluid inclusions could be primary; the ratio of liquid to vapour (L:V) is of ~20%.

SADDLE DOLOMITE

Saddle rhombohedral dolomites contain two-phase aqueous liquid-vapour (LV) fluid inclusion. Inclusions are found in growth bands close to the crystal edges. Therefore data derived from this fluid inclusions represent fluids during the late stages of crystal growth. Fluid inclusions are very small, about 5µ m or less, and have elongated to negative shapes.

It was not possible to do freezing runs and the homogeneization temperatures of fluid inclusions are not precise.

Primary two-phase fluid inclusions parallel to crystal growth zones and have negative crystal shape; L:V is ~10% or less. During heating, the bubble rests imobilized until 87^0C when it starts to move. At 159^{0}C the bubble is small, still visible, but darkening of the crystal suggests overheating.

In another double thin section, primary two-phase fluid inclusions with negative crystal shape were analized. At 114.6^{0}C the bubble starts to move and remains in motion until 231^{0}C. The bubble is visible until 262^{0}C as a black dot but does not move. Darkening of the crystals at 300^{0}C suggesting overheating.

A two-phase secondary fluid inclusion, trapped in a microfracture of saddle dolomite, was analized. During heating the bubble starts to move at 76.4^{0}C and remains in motion until 150^{0}C when the bubble becomes small and dark; at 193^{0}C it disappears and this could be considered the homogeneization temperature. The bubble renucleates as a large black dot during cooling at 71.5^{0}C.

FLUORITE

Fluorite contains a great variety of fluid inclusions including two-phase aqueous liquid-vapour (LV) fluid inclusions and gas-fluid inclusions. Several populations were observed having different shapes and ratio of liquid to vapour; most of them are irregular or globular. Only two-phase fluid inclusion data were analized.

Most of the fluid inclusions are secondary, occur in lines (5 to 10μm) and also occur scattered or roughly in lines (average 40μm) possibly along microfractures; these fluid inclusions are numerous. Isolated fluid inclusions are rare, as big as 60μm, and the bubble can occupy 30 to 40% of the total volume of the fluid inclusion; there is no features suggesting they are related to microfractures.

As fluorite is not related to sulfide minerals, being later than LCC, only data related to homogeneization temperature (Th) are discussed. However the final melting temperature in different populations suggests they are slightly different compositionally. In a general way, salinity is ~10% in secondary fluid inclusions; eutectic temperature ranges from –50 to –55^{0}C characterizing of the H_2O-NaCl-$CaCl_2$ system (Crawford 1981).

Homogeneization temperatures in scattered fluid inclusions vary from 172.5^{0}C to 178.6^{0}C; L:V is of ~20%. Small fluid inclusions in line (L:V ~10%) have homogeneization temperatures of around 155^{0}C. The biggest fluid inclusions are globular, and Th is mostly 165 to 166^{0}C; Th of 189.7 to 190.7^{0}C was also obtained. The liquid to vapour ratio of these fluid inclusions is 30 to 40%.

6.5.1. DISCUSSION

The homogeneization temperatures (Th) of fluid inclusions represent the minimum trapping temperatures and presure corrections should be applied to define the actual trapping temperatures at which LCC, SD and fluorite precipitated, depending at what burial depth they formed. However the burial history of the São Francisco Basin is not well known though we consider the minimum burial depths were about 500 to 2000m, based on the stratigraphic thickness of the basin and later geological history of the region. Also as few data are available from SD, the homogeneization temperatures are not corrected. Thus the real Th of the fluid inclusions would be higher than the reported results.

Although still preliminary, data obtained from SD suggest that the Th's were certainly above 231^{0}C for primary fluid inclusion because the bubble was still in motion. Secondary fluid inclusion shows Th at 193^{0}C.

LCC has lower homogeneization temperatures as compared to SD. Isolated fluid inclusions yielded temperatures of 188 to 189^{0}C. The lowest Th ranged from 108 to 114^{0}C in secondary, in line fluid inclusion. Scattered fluid inclusions have intermediate Th of about 124.5 to 132.5^{0}C. If these isolated fluid inclusions were primary, they would indicate decreasing temperatures from primary to secondary fluid inclusions.

In the Serra do Cantinho Hill, LCC precipitated after SD from fluids with lower temperatures and very low salinities as indicated by bubble contraction during freezing runs (Roedder 1984).

Fluid inclusions in fluorite also suggest a decrease of Th from large, isolated fluid inclusions (189 to 190^{0}C) to scattered fluid inclusions (172.5 to 178.6^{0}C). The lowermost homogeneization temperature was of 155^{0}C, obtained from in line fracture, clearly secondary fluid inclusions. Interestingly though later than LCC, Th values from secondary fluid inclusions in fluorite are higher. This suggests that entrapment or rehomogeneization of secondary fluid inclusions in LCC occurred after fluorite emplacement.

It is important to consider the possibility of the rehomogeneization of fluid inclusions in diagenetic minerals like dolomite, calcite and fluorite. However, as pointed out by Goldstein and Reynolds (1994), at elevated temperatures, all inclusions trapped under the same set of conditions would have the same L:V ratio and would homogenize at similar temperatures when heated.

This assertion is true for fluid inclusion populations studied suggesting that each population formed under specific conditions of entrapment and thus rehomogeneization would be minor in the measured populations. Consistency of L:V ratio is considered by Reynolds and Goldstein (1994) also as being diagnostic of elevated temperature diagenesis and "cannot be confused with other environments of diagenesis". This reinforces our interpretation that the fluid inclusions in fluorite formed during burial.

6.6 SUMMARY AND CONCLUSIONS

The isotopic composition of seawater during deposition of the Sete Lagoas Formation based on this research is:

i) $^{87}Sr/^{86}Sr$ ratio of the seawater defined according to analytical data is estimated to be between 0.7076 and 0.7079.

ii) $\delta^{18}O$ values obtained from basal limestones range from –6.11 to –6.56‰ (mean= -6.39), and are considered to represent the hypothetical Neoproterozoic seawater composition of the Sete Lagoas Formation.

iii) Limestones yields $\delta^{13}C$ values around zero, with mean = 0.42‰. $\delta^{13}C$ values in dolostones varies from 0.76 to 3.39‰ PDB.

Isotopic values of Januária carbonates are compared with basins worldwide in Figure 6.7 from Shields (1999).

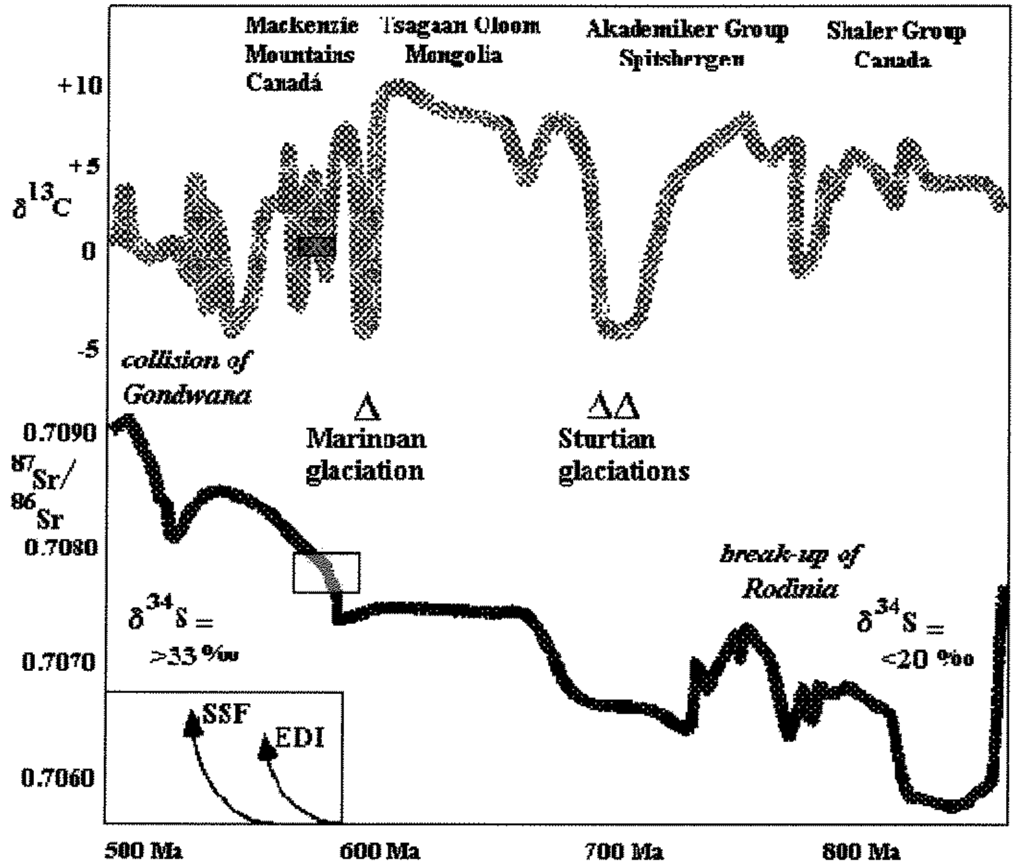


Figure 6.7. $^{87}Sr/^{86}Sr$ seawater composition (*red*) and the mean values of $\delta^{13}C$ (*blue*)of the Sete Lagoas Formation compared with basins worldwide; from Shields (1999).

LIMESTONES

The limestones of Januária region yield δ^{13} C values characteristically around zero, with mean = 0.42‰ (Fig. 6.5). These values are consistent compared with those of the Arcos region.

In the Mina da Bocaina section (Arcos area) C isotope values ranging from 0.47 to 1.28‰ (mean = 0.99‰) were obtained, the slightly higher values are from a microbial buildup in the lower part of the section. Microbial limestones (6 samples) have δ^{13} C values between 1.20 to 1.33 ‰ (mean = 1.26‰); decreasing values occur in calcisiltites with δ^{13} C average of 0.86‰.

The basal limestones in the Januária region show an $^{87}Sr/^{86}Sr$ ratio varying from 0.7076 to 0.7079. These rocks should contain the primary Sr isotopic composition of Neoproterozoic seawater during deposition of the Sete lagoas Formation, provided the Sr isotope ratios have not been alterd during diagenesis.

MICROCRYSTALLINE DOLOMITE

McCD is usually stratiform, early diagenetic and preserves sedimentary structures; and frequently also preserves the internal texture of the allochems. Sr composition of subtidal dolostones from unmineralized areas is slightly higher (0.7085 to 0.7094) than the range of the estimated $^{87}Sr/^{86}Sr$ ratio of the Sete Lagoas Formation seawater (from 0.7076 to 0.7079).

If these microcrystalline dolomites formed from evaporated seawater, the Sr isotope composition should be similar to values of seawater at the time of sediment deposition. Thus, the slightly higher $^{87}Sr/^{86}Sr$ ratios suggest that their original isotopic signatures were partly modified by later diagenetic fluids.

$\delta^{13}C$ values in McCD are highly variable, from 0.76 to 2.85‰.

δ^{18} O values (mean = -4.95) are almost 2‰ heavier than the considered hypothetical seawater suggesting that the dolomitization fluids could be seawater or slightly modified seawater. Microcrystalline dolomite is mainly observed in tidal flat environments, where commonly salinity is higher than normal seawater because of evaporation.

Thus, McCD is interpreted to have formed from modified seawater during seaward progradation of the tidal flats and further modified by later diagenetic fluids as suggested by the Sr isotopic composition.

MEDIUM AND COARSE CRYSTALLINE DOLOMITES

MCD and CCD are late replacement dolostones that crosscut the dolostone and the ooid-intraclast dolostone members (the dolomitic calcarenite member is partly dolomitized) and are intimately associated with VcCD and saddle dolomite near mineralized areas.

$\delta^{18}O$ values are slightly lighter than the McCD dolomite. This depletion of $\delta^{18}O$ could be related to the formation of dolomite at elevated temperatures in a burial environment or resulted from replacement/neomorphism of previous dolomite later affected by diagenetic fluids. MCD and CCD have uniform positive $\delta^{13}C$ values and lack evidences of meteoric diagenesis and thus did not form by action of meteoric waters.

Sr composition of MCD and CCD is more radiogenic than the seawater composition, suggesting that dolomitizing brines were probably allochtonous, having interacted with K-feldspar in crystalline basement rocks or siliciclastic sediments before entering the carbonate units they dolomitized.

Thus MCD and CCD are interpreted as having formed by the neomorphism and/or replacement of preexisting dolomites during burial by migrating fluids that had interacted with K-rich lithologies.

VERY COARSE-CRYSTALLINE (VcCD) AND SADDLE DOLOMITES (SD)

VcCD and SD are frequently associated with each other and hosted in CCD/ MCD. $\delta^{13}C$ values are similar for all of these dolomites. However δ^{18} O values in VcCD and SD are depleted compared with MCD/CCD. VcCD and SD exhibit the lighest $\delta^{18}O$ values in dolomites studied. Dolomites with depleted $\delta^{18}O$ values are interpreted as forming from hydrothermal, high temperature migrating fluids during burial (Morrow 1990; Allan and Wiggins 1993) and from other dolomitizing fluids that differed from those responsible for CCD/MCD generation.

Homogeneization temperature in SD fluid inclusions above 231^0C confirms the presence of high-temperature, hydrothermal fluids during burial.

The Sr composition of the MCD and CCD having VcCD are also more radiogenic than inferred Neoproterozoic seawater, suggesting that dolomitizing brines were allochtonous, and probably had interacted with K-feldspar in basement rocks or siliciclastic sediments before entering the carbonate units they dolomitized.

VERY FINELY CRYSTALLINE DOLOMITE (VfCD)

Fine crystalline dolomite exhibit δ^{18}O values heavier than the hypothetical seawater: -4.48‰ and –5.10‰ PDB but within the range of calculated δ^{18}O values for dolomites that would precipitate form the estimated Neoproterozoic seawater; δ^{13}C values are of 3.39‰ and 3.0‰ PDB.

The Sr composition is more radiogenic than the hypothetic seawater but similar or slightly less radiogenic than fluids generating MCD, CCD and VcCD. No evidence of submarine or subaerial diagenesis was found related to VfCD.

VfCD is interpreted as resulting from chemical and/or chemically induced mechanical disaggregation of the ore-bearing dolomite and its contained ore, based on comparisons with Polish Pb-Zn ore deposits of western Poland (Saas-Gustkiewicz 1996). Chemical desintegration proceeded by partial dissolution of crystal edge and faces (grain-by-grain release of Kendal 1977) resulting in masses of "sanded dolomite" deposited as internal sediments in cavities related to hydrothermal activity.

The sources of this internal sedimentary material (VfCD) are McCD, MCD, CCD, VCD and SD (would correspond to the hydrothermal proto-karst of Saas-Gustkiewicz *op. cit.*). The Sr isotopic signature of VfCD is very similar to that of the previous dolostones making this hypothesis plausible.

The heavy δ^{18}O values found in VfCD are of restricted isotopic composition (Figure 6.5) and could be interpreted as being high salinity and high temperature brines (Hoefs 1997).

Also brines associated with ore mineralization are usually of high salinity; MVT and Irish-Type fluids are typically 10 to 30wt%, disregarding their origin (Sangster and Leach 1995), thus displaying heavy $\delta^{18}O$ values. The heavy $\delta^{18}O$ values could result from formation brines or infiltration of evaporative surface waters that interacted with the previous dolomite. This hypothesis would explain the high $^{87}Sr/^{86}Sr$ ratios compared to hypothetical Neoproterozoic seawater of Sete Lagoas Formation, but compatible with Sr isotopic composition of precursor MCD, CCD, VcCD and SD.

Also the presence of oil inclusions in sphalerite (Chang 1977) as well as in late calcite argue for processes operating during burial. Oil also filled all remaining porosity after fluorite emplacement ending or restrictiong the diagenetic processes.

Summarizing, VfCD is here considered as resulting from high salinity basin brines, but intermediate Sr isotopes, related to mineralizing fluids.

LATE-STAGE COARSE-CRYSTALLINE CALCITE (LCC)

This phase exhibits strongly depleted $\delta^{18}O$ values compared to seawater and to dolomites in the mineralized area, suggesting precipitation from warm basinal fluids of low salinity generated during burial. The contraction of the bubbles in two-phase fluid inclusions during freezing runs indicates low salinity and Th above $108^{0}C$ in late calcite confirms they deposited from warm fluids.

LCC is slightly more radiogenic (0.7090) than the estimated Neoproterozoic seawater of the Sete Lagoas Formation. LCC is late than ore mineral emplacement and contains small dark inclusions.

CHAPTER 7

HYDROTHERMAL ORIGIN OF DISSOLUTION VUGS AND BRECCIAS HOSTING Zn/Ag MINERAL DEPOSITS IN THE JANUÁRIA REGION

7.1 INTRODUCTION

Epigenetic base-metal deposits hosted in carbonate rocks without magmatic connections generally exhibit the same characteristics such as extensive dolomitization, hydrothermal dissolution vugs, dissolution/collapse brecciation and hydrothermal dolomite cement (saddle dolomite). These deposits have been classified as being Mississipi Valley-type (MVT) and Irish-Type.

MVT mineral deposits of different ages and regions are hosted mainly in dolostones and are closely associated with breccias and dissolution vugs. The origin of these solution features has been controversial (Ohle 1985; Sangster 1988). Some workers have related these vugs and breccias to meteoric karst systems or unconformities (Kyle 1981, 1983; Rhodes et al. 1984). Mineralization was considered to be a later, separate diagenetic event.

For most MVT deposits, "support for meteoric dissolution is largely circunstancial and little or no clear-cut evidence has yet been recognized" (Sangster 1988). Others suggested that most dissolution, insofar as the orebodies were concerned, was accomplished by hydrothermal fluids moving along subsurface aquifers (e.g. Sass-Gustkiewicz et al. 1982; Anderson 1983; Ohle 1985; Anderson and Garven 1987; Qing and Mountjoy 1994a,b; Sangster and Leach 1995; Leach et al. 1996).

Irish-Type mineral deposits are also hosted mainly in dolostones associated with important breccias and dissolution vugs (Hitzman and Beaty 1996). Dolostones hosting mineral deposits are mostly regional, a pervasive replacement of medium crystallinity (Braithwaite and Rizzi 1997) and postdate compaction (Gregg et al. 2001). The origin of breccias and dissolution vugs are controversial, being interpreted as produced by in-situ hydrothermal alteration and minor to large scale solution-collapse of older carbonate rocks (Hirtzman and Beaty 1996). Some workers (e.g.Taylor 1984; Andrew 1986) considered the same breccia breccia as synsedimentary, as clearly intraformational conglomerates formed in high intertidal to supratidal environments. Faults and permeable strata would be the main conduits for dolomitizing and mineralizing fluids, though the faults themselves are largely barren of sulfides (Andrew and Ashton 1985 *in* Hitzman and Beaty 1996); less permeable units acting as aquitards provided important control in the extent of dolomitization.

The carbonate rocks of the middle São Francisco valley region, including those of the Januária region, host several small Pb-Zn mineral deposits considered mostly MVT and their host carbonates have also undergone considerable dissolution and brecciation.

Dissolution features are often interpreted as being related to an unconformity and thus resulting from subaerial exposure (Beurlen 1973, Dardenne 1979) and meteoric karst development (Lopes 1979). In the case of fluorite mineralization, Dardenne (1979) considered that breccia development, due to subsurface fluids responsible for mineralization; base-metal concentration was inferred to be synsedimentary or early diagenetic and had to be related to an unconformity. However, Robertson (1963) reported no unconformity suggesting that the hydrothermal fluids may have played a role in the formation of these features.

Authors	**Date**	**Evidence**
Robertson	1963	hydrothermal breccias
Beurlen	1973	intraformational breccia; meteoric karst
Lopes	1979	breccias suggesting meteoric karst

Table 7.1. Various interpretation of carbonate dissolution breccias

In this chapter the processes and fluids responsible for dissolution in the Januária region are outlined and discussed.

Understanding the timing, origin and the extent of dissolution/collapse breccias, as well as the distribution of hydrothermal saddle dolomite are very important because worldwide brecciated carbonates host various sulfide, gas and petroleum deposits. In addition the results of this study have important implications for mineral deposits where hydrothermal dissolution may have been overlooked and/or incorrectly attributed to subaerial dissolution or other sedimentary process.

7.2 DISSOLUTION FEATURES AT THE JANUÁRIA REGION

The origin and timing of dissolution features of Januária is controversial (see Table 7.1); but the origin of dissolution vugs and breccias can be determined by their infilling materials, host-rock lithology, spatial distribution, and diagenetic paragenesis.

	Meteoric dissolution	**Subsurface dissolution**
Material filling dissolution features	Small vugs filled with finely dolomitized sediments on the top of stromatolite reefal barrier (member 5); vadose micritic cementation, tepees and dissolution cracks in the dolomudstone member 7.	VcCD, rhombohedral SD, VfCD, sphalerite, willemite, white SD, LCC, bitumen
Host-rock lithology	Control is related to the stratigraphic position of the host-rock.	Occurs in late replacement dolomites and cements interpreted to be related to the action of warm fluids during burial.
Vertical stratigraphic position of dissolution features	Occurs on the top of stromatolite barrier reefs (stromatolite dolostone member 5) below the hypothetical unconformity that would affect member 6 and on the uppermost layers of small shallowing-upwards cycles making up the dolomudstone member 7: units 7A and 7B..	Occurs in the lower unit (7A) of the dolomudstone member 7 and ooid-intraclast dolostone member 6, crosscutting the hypothetical unconformity above member 6. Locally affects also the dolostone member 4
Diagenetic paragenesis	Predates stylolitization, replacement dolomites and mineralization.	Postdates stylolitization, during and/or after dolomitization and mineralization.

Table 7.2. Comparison of features resulting from meteoric and subsurface dissolution in the Januária region.

In order to determine how much dissolution resulted from the action of meteoric waters during subaerial exposure affecting the carbonate sediments making up the intermediate shallowing-upwards succession (this reseach) geological sections were studied in mineralized and barren areas, located more than 20km away from mineral deposits.

As late diagenesis, especially dolomitization and mineralization greatly obscures the earlier diagenetic features, the influence of late-stage hydrothermal fluids relative to over barren carbonates should be easier to recognize. If dissolution was mainly by meteoric waters, similar features should also be observed in mineralized and barren areas, because the subaerial exposure affecting carbonates of the intermediate shallowing-upwards succession represents a regional subaerial exposure.

VUG AND BRECCIA FILLINGS

Most authors (see Table 7.1) interpret the dissolution/collapse breccias of the middle São Francisco as resulting from meteoric waters (meteoric karst) due to subaerial exposure affecting the ooid-intraclast dolostone member 6. If this was true, the vertical distribution of the dissolution features should be stratigraphically restricted to zones below the disconformity inferred to be the meteoric karst surface, and thus would not affect sediments of the dolomudstone member. However, large-scale brecciation (the "confuse fracturing" of Cassedanne 1972) is visible elsewhere in the dolomudstone member, especially in its lowermost part.

Dissolution features resulting from meteoric diagenesis are

1. small vugs on the top of stromatolitic reefal barrier that were sporadically exposed and filled with fine dolomite (McCD); these occur in the stromatolite dolostone member 5
2. vadose cements, tepees and desiccation cracks, from intertidal to supratidal environments, that are widespread in the dolomudstone member 7 (units 7A and 7B).

The characteristic karst landscape produced and controlled by migration of calcium carbonate in meteoric waters has not been recognized in the area. Old surface landforms (e.g. lapies, dolinas) and subterranean landforms (e.g. pores, caves, vugs, etc), speleothems (e. g. stalactites, stalagmites, cave pearls, etc), collapse structures as well as meniscus and gravitational cements

(Esteban and Klappa 1983), indicators of a vadose zone in association with other karst features, were not found. Evidence of terra rossa development is lacking.

The large-scale dissolution in the Januária region on the contrary, occurred above replacement dolomites (mostly above late replacement but also affecting early replacement dolomites). Dissolution/collapse brecciation created open spaces as vugs, cavities of different sizes, fracturing and dissolution features along bedding-planes that were first cemented by saddle dolomite (rhombohedral form) and VcCD, the last being more common in barren areas (Fig.6.2a,b,c).

Recurrent dissolution/brecciation affected preexistent breccias generating new vugs and cavities filled by subsequent diagenetic products, mainly VfCD (Fig. 6.4 and 7.1), sulfide and silicate Zn minerals (Fig. 5.3 c, d), white SD (Fig. 5.3b), LCC (Fig. 5.4a), fluorite (Fig. 5.4b) and bitumen (Fig. 5.4d).

Geopetal dolomite cements are represented by white saddle dolomite (Fig. 5.3b). White saddle and anhedral dolomites (Fig. 6.2d) apparently were not affected by brecciation.

It is interesting to note that in some areas whereVfCD is predominant (Fig 7.1a), breccia bodies are usually larger, almost vertical and discordant in relation to the regional dissolution/collapse breccia level (this was observed at Serrotinho, and possibly occurs also at Capão do Porco Hill). VfCD may display lamination, occasionally normal grading, and is similar to the sanded dolomites of Kendal (1977) or the internal sediments of Rhodes et al (1984). VfCD fills cavities and may contain corroded and/or broken peaces of older dolomites, as replacement dolomites, VcCD, and rhombohedral SD (Fig. 7.1b). Clasts of VfCD in are uncommon.

Brecciated areas of VfCD are cemented by sphalerite (Fig 7.1c). Laterally, the vertical dissolution/collapse breccia body containing large amounts of VfCD gradually disappears in the regional dissolution/collapse breccia level. Cavities filled with VfCD could represent subsurface caves.

Thus, vugs and breccia fillings related to dissolution/collapse breccia are very diversified indicating a complex diagenetic evolution. Small vugs adjacent to subaerial exposure surfaces do not exhibit these features. These vugs are affected only by small fractures filled with sparry calcite, and high amplitude, non-parallel bedding, late stylolites.

Figure 7.1a-7.1c Mineralized dissolution/collapse breccia.

a) Outcrop of mineralized dissolution/collapse breccia. Intraclasts in the brecciated dolostone are visible and of different sizes. Location: Ooid-intraclast dolostone member, Serrotinho.

b) Thin section photomicrograph of dissolution/collapse breccia (a) showing very fine euhedral dolomite crystals (VfCD) cementing clasts made up of CCD, VcCD and rhomboedral saddle dolomite. Dark areas are bitumen-rich. Plane light. Location: Ooid-intraclast dolostone member, Serrotinho.

c) Dissolution/collapse breccia (a) with sphalerite cementing clasts mostly made up of VfCD or filling open spaces. Vertical dimension of the picture is of ~30cm. Location: Ooid-intraclast dolostone member, Serrotinho area.

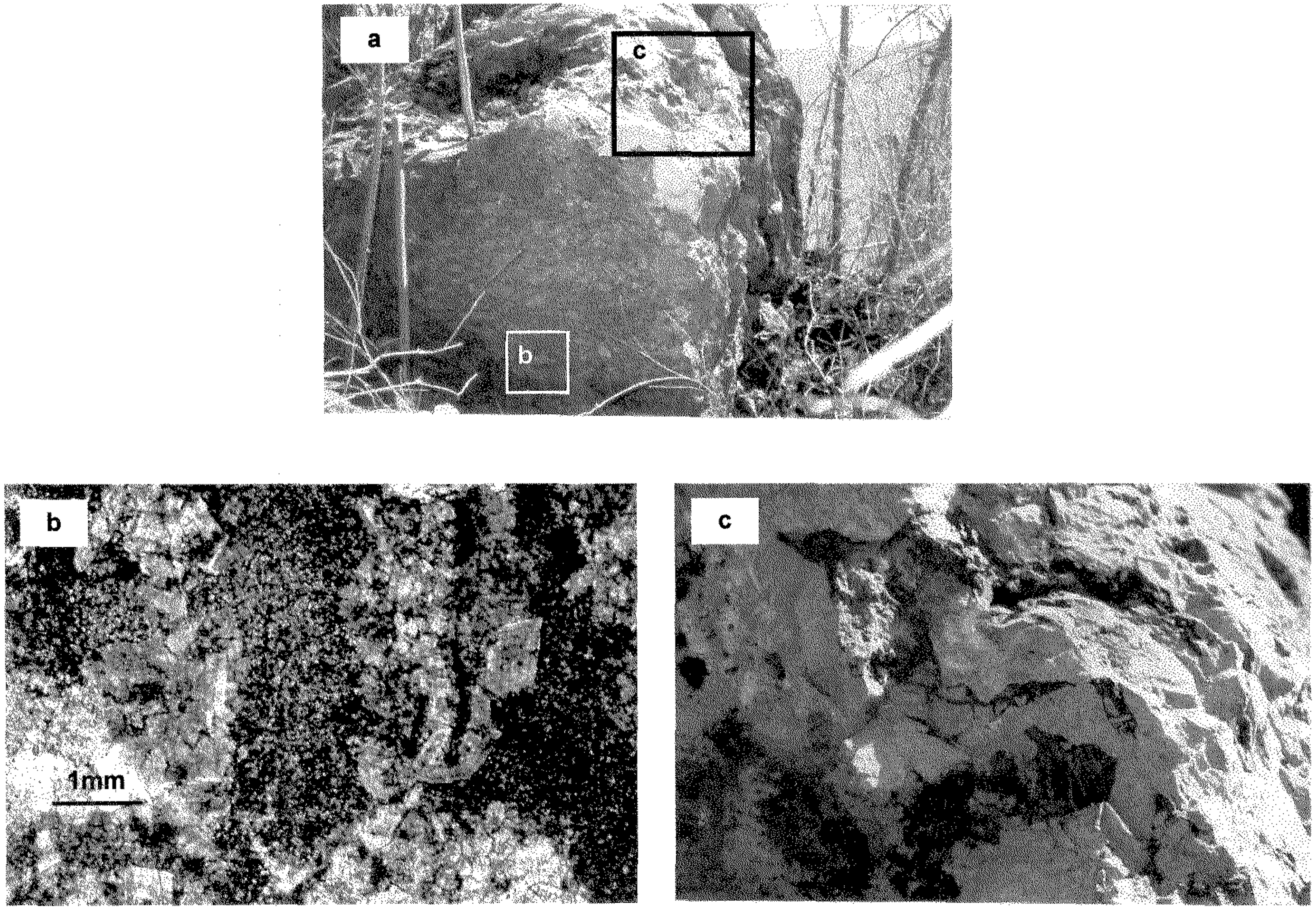


Figure 7.1. Mineralized dissolution/collapse breccia.

SPATIAL DISTRIBUTION OF DISSOLUTION FEATURES

Dissolution features are regionally widespread, occurring for more than 200 km from Januária northwards. The trend and the main controls of fluid flow responsible for dolomitization, dissolution collapse brecciation, and mineralal emplacement are not well established, due to the scarcity of data. The dissolution/collapse breccias occur as an extensive stratabound unit in the left margin of the São Francisco River valley and contain scattered Zn (Ag) and Pb mineralization. Apparently the same breciated level is also present in the eastern margin of the river; Abreu-Lima (1997) mentions the presence in this region of breccias (of unespecified type) in the same stratigraphic interval, in subsurface.

If dissolution vugs in the studied area were caused mainly by meteoric waters during a possible subaerial exposure affecting the ooid-intaclast dolostone member 6 (see chapter 4 and item 7.1), these features should be restricted to units below the member 6. However, brecciation with local development of dissolution/collapse breccia with associated VcCD and rhombohedral saddle dolomite crosscut the hypothetical unconformity, and affects the lowermost part of the unit 7A of the dolomudstone member 7, stratigraphically above. Besides that, the characteristic karst landscape is not recognized and there is no evidence of terra rossa development.

Field data and petrographic studies of the carbonate rocks indicate that most of the dissolution/collapse breccias and infilling products do not result from meteoric diagenesis (see chapters 4, 5 and 6 and table 7.2).

Regionally extensive brecciation and dissolution affects the stratigraphic interval extending from the dolostone member 4 to the lowermost unit (7A) of the dolomudstone member 7 (Figure 7.2). Stromatolite bioherms lack evidence of dissolution possibly due to their early lithification.

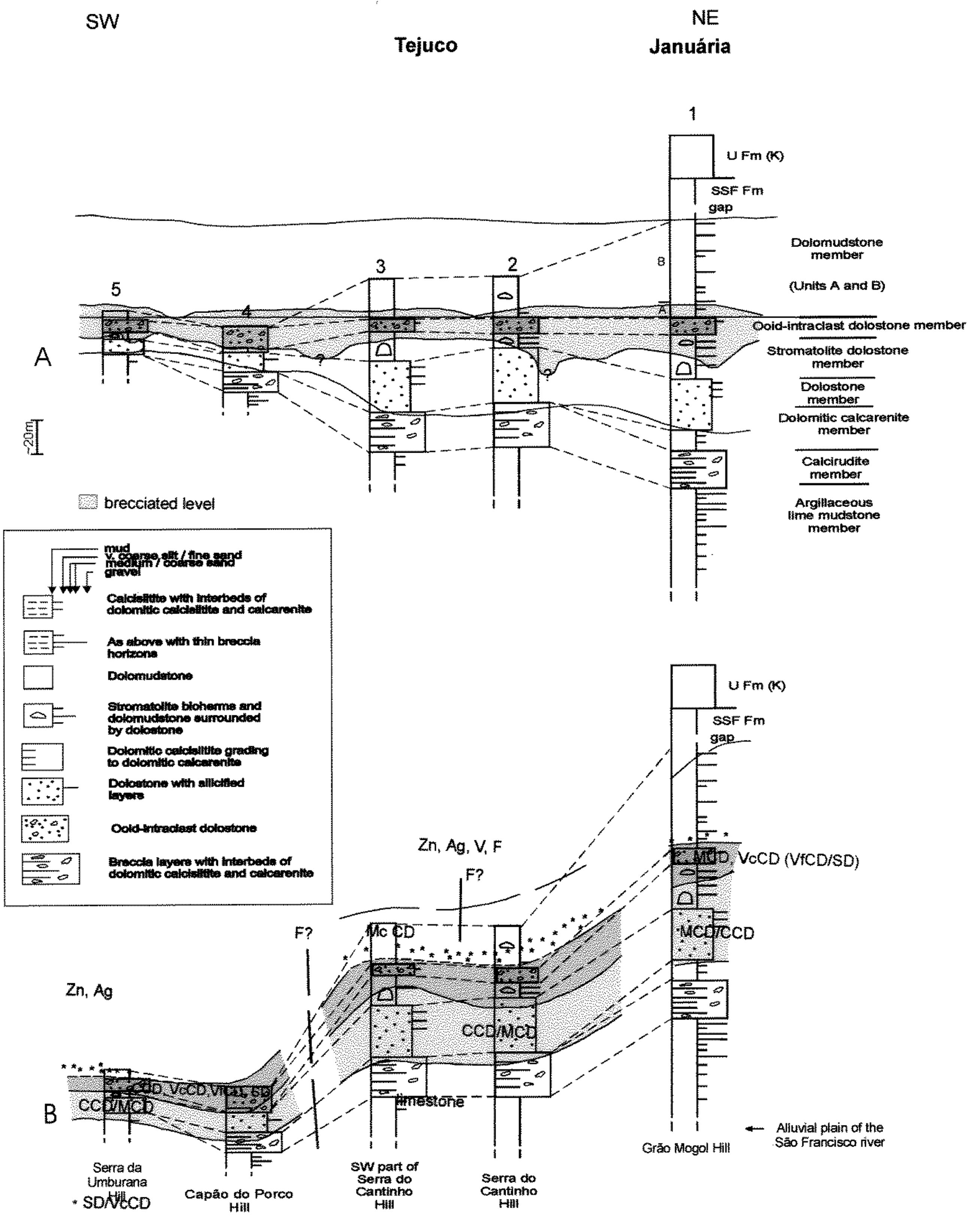
Dissolution/collapse breccias and mineralization observed in the Serra da Umburana Hill crosscut the hypothetical unconformity developed above the member 6 and affect lithofacies of the ooid-intaclast dolostone member 6 and the dolomudstone member 7.

Figure 7.2a -7.2b Stratigraphic position of the brecciated level.

A) The position of the brecciated level related to the original stratigraphic position of the sediments. The level used as reference is the lower contact of the dolomudstone member 7.

B) The brecciated level as it occurs in outcrops; the level used as reference is the alluvial plain of the São Francisco River valley.

- - presence of rhombohedral SD.


SW
Tejuco
NE
Januária
U Fm (K)
SSF Fm
gap
Dolomudstone member
(Units A and B)
Ooid-intraclast dolostone member
Stromatolite dolostone member
Dolostone member
Dolomitic calcarenite member
Calcirudite member
Argillaceous lime mudstone member
A
B
~20m
brecciated level
mud
v. coarse silt / fine sand
medium / coarse sand
gravel
Calcisiltite with interbeds of dolomitic calcisiltite and calcarenite
As above with thin breccia horizons
Dolomudstone
Stromatolite bioherms and dolomudstone surrounded by dolostone
Dolomitic calcisiltite grading to dolomitic calcarenite
Dolostone with silicified layers
Ooid-intraclast dolostone
Breccia layers with interbeds of dolomitic calcisiltite and calcarenite
Zn, Ag, V, F
F?
Zn, Ag
MCD, VcCD (VfCD/SD)
MCD/CCD
Mc CD
CCD/MCD
limestone
Serra da Umburana Hill
* SD/VcCD
Capão do Porco Hill
SW part of Serra do Cantinho Hill
Serra do Cantinho Hill
Grão Mogol Hill
Alluvial plain of the São Francisco river

Small fractures observed at Serra do Cantinho Hill crosscut the members 6 and 7 (Fig.7.3a) and are filled with zinc-rich rhombohedral SD, that also cements open spaces along bedding-planes in the lowemost part of the unit 7A (Fig. 7.3b) and small vugs in the ooid-intraclast member 6 (arrow). In the member 6, later dissolution affects the replacement dolomites as well as the rhombohedral SD generating new vugs filled with needles of zinc silicate (Fig. 7.3c).

These facts clearly demonstrate that dissolution postdates deposition of the dolomudstone member 7 and is not related to an unconformity developed above the member 6, stratigraphically below.

Thus, despite that much of the dissolution and mineralization occur below the dolomudstones, saddle dolomites as well as brecciation/dissolution and mineralization crosscut the presumed subaerial exposure surface and underlying meteoric karst, extending into overlying sediments of the dolomudstone member 7.

Furthermore, large-scale, regional dissolution seems closely associated with the occurrence of dolomite cements, especially rhombohedral saddle dolomite and in barren areas also with VcCD, because usually these are the first cements to fill vugs and breccias. A similar conclusion was attained by Qing (1991) and Qing and Mountjoy (1994a,b) in studying dolomites that host important MVT mineral deposit at Pine Point, Canada.

Dissolution occurred in several phases and the spatial distribution of large-scale dissolution features clearly postdates the subaerial exposure of the carbonate platform that ended the intermediate shallowing-upwards succession (this research).

Fluid inclusion data from rhombohedral saddle dolomites suggest that they were precipitated at temperatures above 230^0C; light $\delta^{18}O$ values varying from –8.40 to –9.62‰ (mean = -9.09‰) also suggest deposition of rhombohedral SD and VcCD by warm fluids under burial condition.

Figure 7.3a - 7.3c Brecciation affecting the unit 7A of the dolomudstone member 6 and ooid-intraclast dolostone member 6. Fractuing, disolution and dolomite cementation.

a) Small fracture cutting across the ooid-intraclast dolostone member 6 and dolomudstone 7 (unit 7A) are filled with saddle dolomite. Dissolution along bedding-planes in the unit 7A are filled with rhombohedral from of SD (arrow); in the member 6, small vugs (arrow)are also filled with SD (rhombohedral form). Location: contact between the Ooid-intraclast dolostone member 6 (lowermost part of the outcrop) and the Dolomudstone 7 (uppermost part of the outcrop), Serra do Cantinho Hill.

b) Thin section photomicrograph of rhombohedral saddle form filling open-spaces along small fracture, bedding-planes. Photomicrograph is ~1.5mm high. Plane light. Location: Dolomudstone member 7, unit 7A, Serra do Cantinho Hill.

c) Thin section photomicrograph ofreplacement dolomite (CCD) showing a vug filled with rhombohedral SD, later affected by dissolution; the new vug is filled with needles of Zn silicate (willemite-arrow). Plane light. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill.

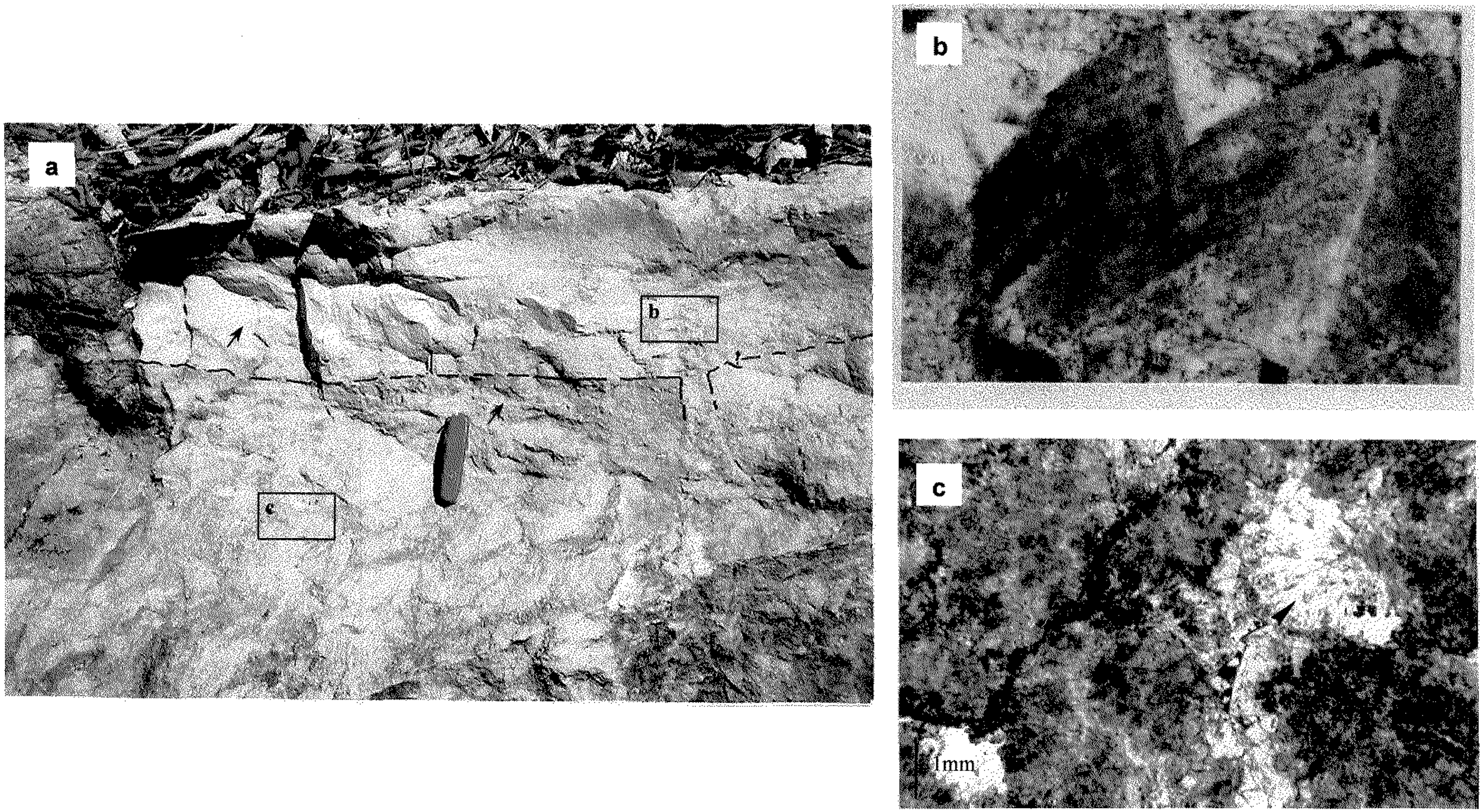


Figure 7.3. Brecciation affecting the unit 7A of the dolomudstone member 7, and ooid-intraclast dolostone member 6. Fracturing, dissolution, and dolomite cementation.

It is interesting to mention that breccia-types are not uniformly distributed in the study area; lateral variation is unpredictable, but a rough vertical zonation can be recognized; brecciation, collapse, dissolution/collapse brecciation and cementation increase downwards (Fig.7.4).

The thickness of the brecciated interval is not uniform, and seems to increase near mineralized areas; however, in barren areas such as the Gão Mogol Hill, dissolution/collapse breccias attain more than 15 meters vertically.

As to the vertical zonation, the brecciated level has on the top an outer shell made up of brecciated dolomudstones (affecting especially the lowemost part of the unit 7A) similar to crackle breccias; open spaces are mostly filled with rhombohedral SD and LCC (Fig. 7.5a, b). However, in some areas, as in the Serra da Umburana Hill, dolomudstones exhibit mineralized dissolution/collapse breccia; in that area the infilling products of the cavities include clasts of replacement dolostones, rhombohedral SD, and VfCD cemented by sphalerite, later cut by LCC (7.5c)

Crackle breccias grade downwards into dissolution/collapse breccias but fragments immediately below the crackle breccia usually have sharp boundaries and their position commonly suggests fragmentation and collapse (Fig.7.6a); clasts are dm to cm across and cemented mostly by SD and VcCD, the later being more common in barren areas. Where present, this level is about one meter thick and occurs along the contact between the ooid-intraclast dolostones and the lowemost part of the dolomudstone unit 7A.

Downwards, the majority of breccia clasts are about cm to dm in dimension, and in mineralized areas, most of the dissolution/collapse breccias fragments have rounded edges in outcrops; in fresh samples clasts are not so evident (Fig. 7.6b). These breccias are made up of clasts of replacement dolomites (CCD/MCD), clasts to pseudo-clasts of very coarse dolostones and well-rounded clasts of dolomudstone (VcCD and SD), rombohedral saddle dolomite, VfCD, sphalerite, LCC and bitumen. Dolomite cements as VcCD, rombohedral SD and VfCD are affected by dissolution, and broken with new vugs filled with new diagenetic products as sphalerite, willemite (needles), white saddle dolomite, calcite, fluorite and bitumen, indicating that dissolution and brecciation were long continued, especially in and around mineralized areas.

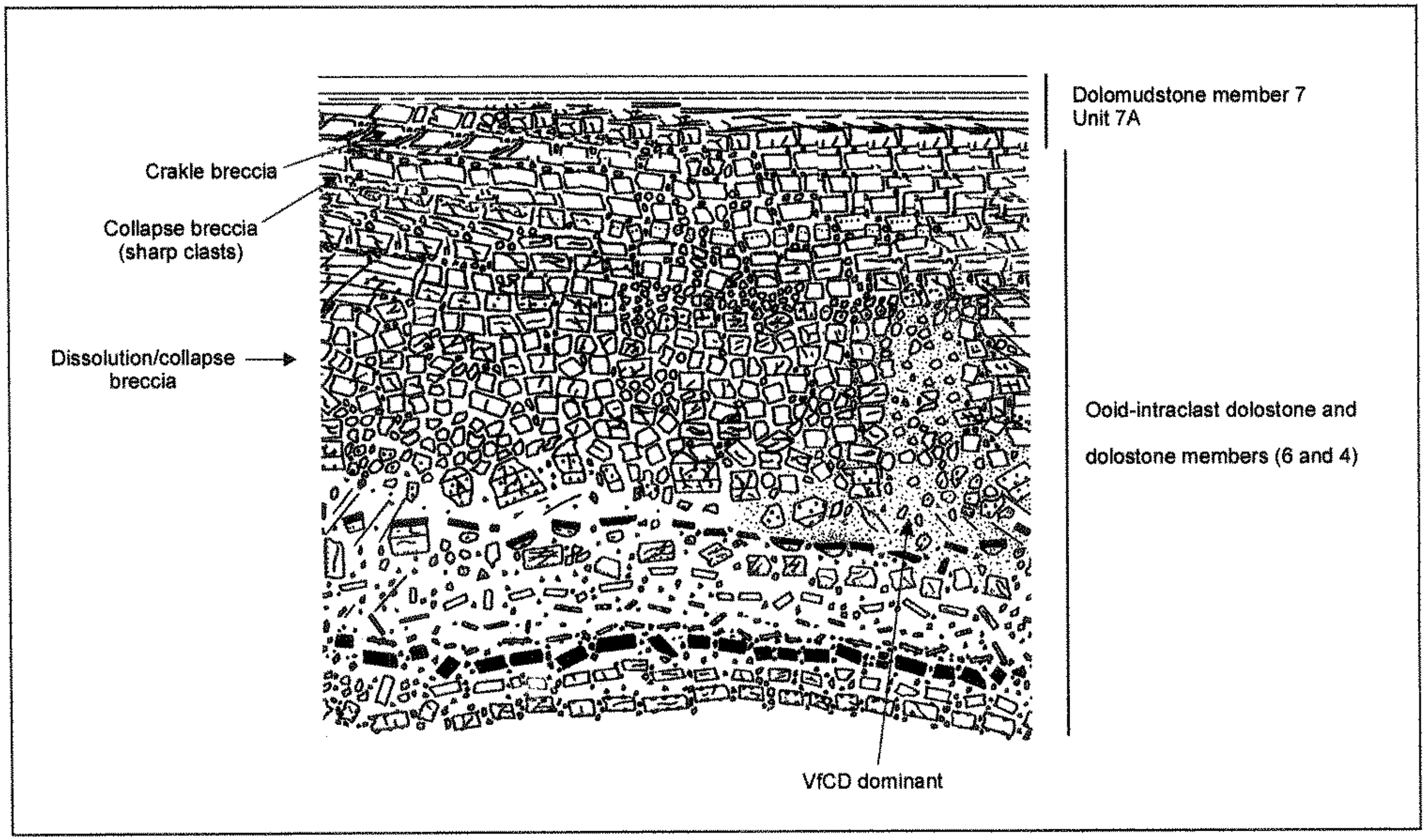


Figure 7.4. The brecciated dolostone level in the Januária region: vertical zoning and lateral variation. (Adapted from Ohle 1985)

Figure 7.5a – 7.5c Brecciated dolostone-dolomudstone member 7, unit 7A.

a) Crackle breccias commonly found in the lowermost part of the dolomudstone member 7, (unit 7A). This type of breccia are observed in the whole area. Location: Dolomudstone member 7, Grão Mogol Hill.

b) Cracke breccias and collapse breccia affecting the lowermost part of the dolomudstone member 7 (unit 7A) and the uppermost part of the ooid-intraclast dolostone member 6. Planar-parallel and low-angle cross lamination are visible in uppermost part of the outcrop (dolomudstone member 7). Location: Ooid-intraclast dolostone member 6 and Dolomudstone member 7 (unit 7A), southwestern part of the Serra do Cantinho Hill.

c) Dissolution/collapse brecciation in mineralized area, affecting the unit 7A of the dolomudstone member 7. Location: Dolomudstone member 7 (unit 7A), Serra da Umburana Hill.

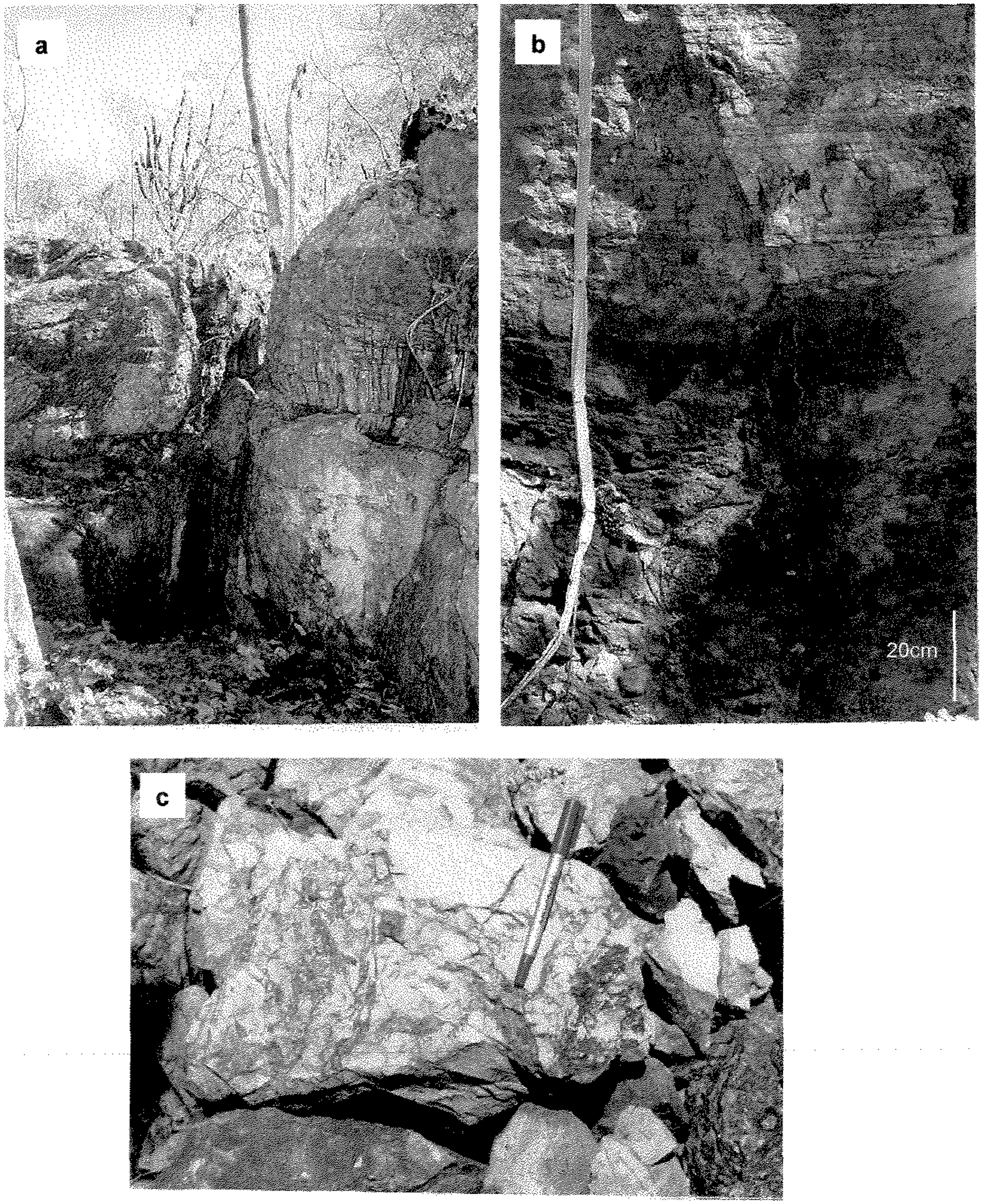


Figure 7.5. Brecciated dolostone - dolomudstone member 7, unit 7A.

Figure 7.6a -7.6c Brecciated dolostone: ooid-intaclast dolostone member 6, and dolostone member 4.

a) Outcrop of collapse breccia with sharp clasts affecting the uppermost part of the ooid-intraclast dolostone member 6. Dolomite cement is rhombohedral SD. Location: Ooid-intraclast dolostone member 6, Serra do Cantinho Hill.

b) Close view of dissolution/collapse breccia in mineralized area; brecciated and collapsed portions are quite visible in weathered surface; on freshly broken surface the dolostone is almost homogeneous, and brecciated portions not always apparent. This type of breccia is more commonly developed over the ooid-intraclast dolostone member 6. Location: Ooid-intraclast dolostone member 6, Imbuzeiro mine, Serra do Cantinho Hill.

c) Apparently homogeneous dolostone with remains of cross-bedding, in fact ghost breccias resulting from chemical dissolution of previously brecciated dolostones. Clasts are only observable under microscope or CL. Location: uppermost part of the Dolostone member 4 and lowermost part of the Ooid-intraclast dolostone member 6, Grão Mogol Hill.

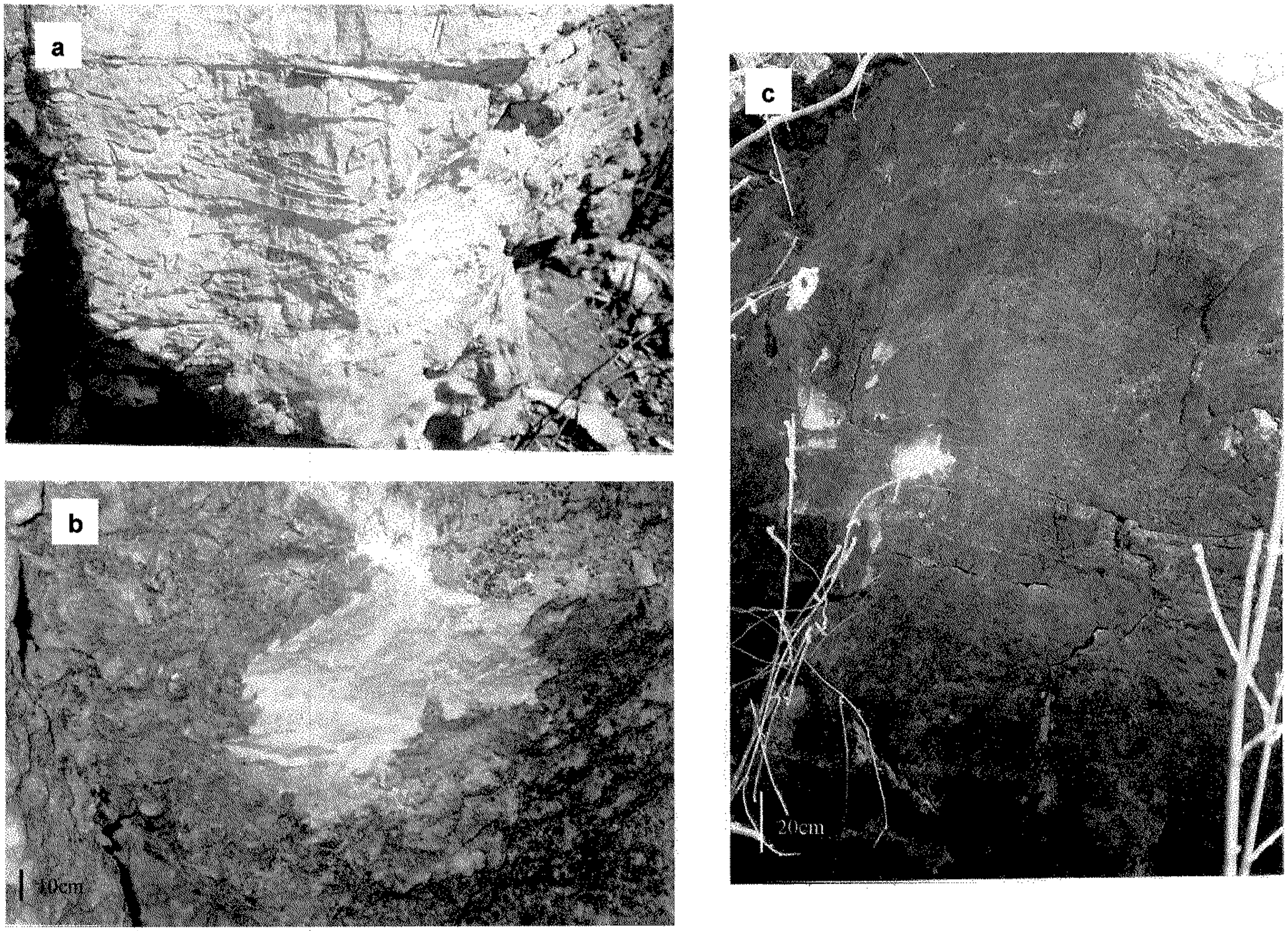


Figure 7.6. Brecciated dolostone: ooid-intraclast dolostone member 6, and dolostone member 4.

Locally, a special type of "breccia" is recognized only under microscope or CL and named ghost breccias. These "breccias" are interpreted as resulting from chemical dissolution of previously brecciated dolomites (Ohle 1985). In some cases only relics of sedimentary structures are observed in the "homogeneous" dolostone (Fig. 7.6c).

Breccia types	**Filling products**	**Affected member**
Crackle breccia	SD in smal fractures and along plane bedding	Lowermost part of the dolomudstone member 7.
Collapse breccia with sharp fragments	Clasts cemented by VcCD and SD	Affects the lowermost part of the unit 7A (dolomudstone member 7) and the uppermost part of the ooid-intraclast dolostone member 6.
Dissolution/collapse breccias	Dissolution of MCD/CCD; relics of sedimentary structures; clasts with rounded edge or not well defined; recurrent dissolutions and pores filled with sphalerite, willemite, white SD, LCC, fluorite and bitumen. Some areas are iron oxide-rich.	Mostly ooid-intraclast dolostone member 6 but also locally the lowermost part of the unit 7A (dolomudstone member 7) as in the Serra da Umburana Hill.
Dissolution/collapse breccia – VfCD dominant	VfCD fills cavities of different sizes cementing clasts of previous dolomites; lamination is common, normal grading rare, brecciation and sphalerite cementing clasts of previous dolomites. Cavities with VfCD are commonly iron oxide poor.	Mostly coarser units of the ooid-intraclast dolostone member 6.
Ghosts breccias	Dolomitization is so intense that clasts are no longer identified, the dolostone seems homogeneous; rare remains of sedimentary structures are preserved	Ooid-intraclast dolostone member 6

Table 7.3. Summary of the main breccia-types and filling products.

Thus, the main dissolution features in the sudied area are dissolution/collapse breccias forming a regionally extensive stratabound level affecting the interval extending from the dolostone member 4 to the dolomudstone member 7 (mostly the lowemost part of the unit 7A). Field data and petrographic studies of the carbonate rocks indicate that most of the vugs and pores with the infilling sediment are related to dissolution/collapse breccia that occurred under burial, due to the action of warm fluids and do not result from meteoric diagenesis related to subaerial unconformity.

7.3 DISCUSSION

The question of how extensive dissolution can occur in subsurface is matter of discussion, especially after Mazzulo and Harris (1992) showed that similar features may develop in meteoric as well as in subsurface (mesodiagenetic) environments. Qing and Mountjoy (1994b) discussing subaerial versus burial dissolution at Pine Point consider that because karst features are commonly observed today in many carbonate areas, "geologists tend to interpret secondary dissolution vugs, caverns and breccias as resulting from meteoric dissolution".

Besides this, several authors have documented subsurface dissolution in carbonate rocks, in association or not with mineralizing fluids (e.g. Sawkins 1969; Stanton, 1972; Sass-Gustkiewicz et al. 1982; Ohle 1985; Babalocwicz et al. 1987; Dravis and Muir 1991; Mountjoy and Halim Dihardja 1991; Mazzulo and Harris 1992, Qing and Mountjoy 1994b).

The interpretation of a meteoric origin for the dissolution vugs and breccias occurring at the middle São Francisco valley region with concomitant development of a meteoric karst was based mainly on the earlier publications of Beurlen (1973), Dardenne (1979) and Lopes (1979). These authors consider the presence of dolomudstone with planar-bedding blanketing brecciated areas with remains of planar and trough cross bedding with small pockets of fine sediment in the middle of breccias, as an indicator of subaerial exposure. The hypothetical subaerial exposure would occur above the ooid-intraclast dolostone member 6 (Unit D of Dardenne op. cit.).

Robertson (1963) working in the same area did not observet this unconformity and explained the breccias as being a product of hydrothermal alteration.

Undoubtedly meteoric dissolution occurred but it is mostly related to the subaerial exposure which took place above the unit 7A of the dolomudstone member that ended the intermediate shallowing-upwards succession or to small shallowing-upwards cycles making up the upper shallowing-upwards succession (unit B).

Meteoric diagenetic features are small vugs on the top of the reefal stromatolites, tepees, micritic vadose cements and desiccation cracks developed in intertidal to supratidal environments; stromatolite bioherms developed as reefal barriers, and reached the sea level, being intermittently exposed (see chapters 4 and 5). No evidences suggesting subaerial exposure below the ooid-intraclast dolostone member 6 were found; features suggesting old karst landforms, caliche facies and terra rossa are lacking.

If a subaerial exposure occurred above the member 4, dissolution features should be restricted to zones below the unconformity represented by the alleged meteoric karst surface, and would not affect sediments of the dolomudstone member 7. However, large-scale brecciation with development of crackle breccia ("the confuse fracturing" of Cassedanne 1972) is visible elsewhere and affects in particular the lowermost part of the unit (7A) of the dolomudstone member 7 crosscutting the presumed unconformity (see Fig. 7.1c and 6.4a). The fracturing with crackle breccia development possibly results from hydrostatic pressure of ascending fluids over dolomudstones that acted as aquitards; cements are mostly VcCD, rhombohedral SD and LCC. In some mineralized areas, as in Serra da Umburana Hill, instead of crackle breccias, dolomudstones (McCD and CpCD) exhibit well developed dissolution/collapse breccias with clasts of McCD, rhombohedral SD, VfCD, and sulfide ore minerals.

Undoubtedly the large-scale dissolution and brecciation that hosts Zn/Ag deposits in the Januária region were produced by subsurface warm fluids, during burial.

The following evidences support a subsurface origin for the large-scale dissolution in the study area:

1. Large-scale dissolution features occur continuously across the ooid-intraclast dolomudstone and dolomudstone members (6 and 7) and thus it is not related to a presumed meteoric karst developed above the ooid-intraclast dolostone member 6.
2. Diagnostic meteoric karst features such as caves, speleothems, vadose cements and terra rossa (Esteban and Klappa 1983; James and Choquette 1990) are not found in the dissolution/collapse breccia layer.

3. The angular shapes of some breccias fragments indicate they formed after lithification.
4. Dissolution and brecciation postdate stylolites and late dolomite replacement.
5. The dissolution/collapse breccia hosting sulfide minerals result from several stages of brecciation and dissolution, as discussed below.
6. Dissolution also postdates the main phase of mineralization as attested by the presence of iron-rich white saddle dolomite cement in old breccias; previous diagenetic phases as rhombohedral saddle dolomite, sphalerite and willemite are iron-poor.
7. Fluid inclusion (Chapter 6) analysis also indicates that dissolution of replacement dolomites and cementation of rhombohedral SD occurred under high temperatures, during burial.

Thus, late subsurface events better explain the large-scale dissolution features, dolomitization and mineralization that occur in the ooid-intraclast and dolomudstone members (6 and 7).

The absence of sulfide minerals associated with zinc-rich rhombohedral saddle dolomite suggests that the initial fluids were dolomite-stable, zinc-rich (see Chapter 3) and poor in reduced sulphur (Leach et al. 1996).

POTENTIAL PROCESSES OF DISSOLUTION

The main dissolution processes associated with ore deposition are related to acidity generated by H2S, sulphate reduction, and /or diagenesis of organic matter before and during mineralization (refs. Qing and Mountjoy 1994a; Krebs and Mcqueen 1984; Machel 1987, 2001).

Acidity generated by H_2S: This model was first outlined by Beales and Jackson (1966) and modified by Anderson (1983) and Anderson and Garven (1987). This process explains precipitation and dissolution of dolomite cements in a brine containing sulfides. H_2S dissolved in brines generates acid either by precipitating sulfide or through oxidation of the pore waters generating sulphate, thus causing dissolution and brecciation of the carbonate rocks. If sulphate reduction started before the arrival of metal-bearing brines, oxidation of H_2S generated during sulphate reduction in the pore fluids may have cause pre-mineralization dissolution and brecciation:

$$H_2S_{(g)} + 2O_{2(g)} = SO4^{2-}_{(aq)} + 2H3O^{+}_{(aq)}$$

According to these authors, sulfide precipitation is an acid-generating process, which inevitably causes dissolution vugs and breccias in the host carbonate rocks. The basic equation is:

$$Zn^{2+}_{(aq)} + H_2S_{(g)} = ZnS_{(s)} + H_3O^{+}_{(aq)}$$

Sulphate Reduction (TSR): This model explains the dissolution associated with saddle dolomites in areas where sulfide minerals are absent or rare (Anderson 1983; Anderson & Garven 1987; Krouse et al. 1988; Reimer and Teare 1992; Machel 2001). The basic equation is:

$$2CaSO_{4\,(s)} + 2CH_{4\,(g)} = Ca,Mg\,(CO_3)_{2\,(s)} + Ca^{2+}_{(aq)} + 2H_2S_{(g)} + 2\,H_2O_{(l)}.$$

Reimer and Teare (1992) proposed that TSR was the principal diagenetic mechanism that created widespread hydrothermal dolostone reservoirs for both natural gas and sulfide minerals. TSR would initiate and sustain the dolomitization reaction, and consequently the dissolution vugs and breccias associated with the saddle dolomite wouldn't necessarily linked to the sulfide mineralization. Acid solutions would be the main responsible for dissolution of carbonate rocks.

Organic Matter Alteration: The thermal alteration of organic matter by hydrothermal solutions could cause a diagenetic sequence of carbonate dissolution, precipitation and renewed dissolution (Spirakis and Heyl 1988, 1990).

The initial dissolution is related to the production of organic acids resulting from heating of organic matter normally with increasing burial. As heating continues, organic acids after reacting with carbonates form carbon dioxide and methane.

Addition of carbon dioxide to a solution with an organic-acid pH buffer decreases the solubility of carbonates causing carbonate precipitation.

At still higher temperatures, organic acids quickly degrade, so that the pH buffer is lost. Without a buffer, the continual addition of carbon dioxide lowers the pH, and causes carbonate dissolution (Spirakis and Heyl 1988, 1990).

Cooling of CO_2-rich Warm Brines: This model explains the formation of the hydrothermal cave system and precipitation of the saddle dolomite. The source of CO_2 would be organic matter, dissolved organic species and dissolution of carbonate minerals (Machel 1987, Spirakis and Heyl 1988).

The principle of this theory is that at a given P_{CO2}, the saturation of dissolved carbonates in solution increases as temperature decreases. Based on that, cooling, e.g. by updip flow of CO_2-rich brines, may result in extensive solution of carbonate rock forming hydrothermal cave systems (Bakalocwicz et al. 1987; Qing and Mountjoy 1994a). However, if basinal CO2-rich fluids moved updip along regional aquifers to shallower depths, the decrease of hydrostatic pressure in rising basinal fluids would cause partial degassing of CO_2, resulting in precipitation of hydrothermal dolomites and calcites. This would account for regionally extensive saddle dolomite cementation that is genetically and spatially associated with localized MVT deposits (Leach et al. 1996).

All of the above mentioned processes could be responsible for the extensive dissolution features commonly observed in mineral deposits hosted in carbonate rocks, mainly in dolostones. Some of these processes certainly were responsible for the generation of dissolution vugs that hosts ore minerals in the Januária region. This mineralization is not related to an extensive meteoric karst horizon but rather occurred much later, during burial, when hydrothermal fluids invaded the area.

This accounts for the presence of rhombohedral saddle dolomite and sulfide minerals both above and below the supposed subaerial exposure levels. Therefore the role of the subaerial exposure with respect to karst and solution features development has been overemphasized in the study area.

In terms of the majority of dissolution vugs and breccias formed during the main dissolution event were not controlled by a meteoric karst but rather were generated later when hydrothermal fluids invaded the middle São Francisco valley area. The key evidence for this is the presence of saddle dolomite and sulfide minerals both above and below the hypothetical meteoric karst surface always associated with dissolution/collapse breccia. Also late replacement dolomites crosscut the hypothetical meteoric karst surface and affect partly the dolomudstone member at Grão Mogol and Serra da Umburana Hills.

Stratigraphically above the ooid-intraclast dolostone member 6, lithofacies of the unit 7A of the dolomudstone member 7 formed a relatively impermeable barrier preventing hydrothermal fluid to flow up into overlying muddy sediments. Because of this most, of the dissolution occurs below the dolomudstone member. However, as already discussed, hydrothermal fluids breached the dolomudstone cover resulting in brecciation and dissolution/collapse breccia extending between the dolomudstone and ooid-intraclast dolostone member, locally 2m above the suggested meteoric karst surface.

It is unlike that the saddle dolomite above the dolomudstone member formed later than the saddle dolomite below it. Their similar geochemical signatures (e.g. δ^{18} O, δ^{13}C and $^{87}Sr/^{86}Sr$) suggest that these saddle dolomites formed during the same event from similar fluids. Similarly, the associated dissolution event that occurs below and above the dolomudstone member may have been produced by similar solutions during one or more major dissolution event.

TIMING OF DISSOLUTION

Petrographic evidence suggests that dissolution and brecciation postdate early stylolitization. Low amplitude, early stylolites are mostly absent in the dolostones but can be observed in breccia clasts, indicating that brecciation occurred after the formation of these stylolites. Thus, early stylolites predate medium-coarse dolomite replacement (Fig. 5.2d) and brecciation. High-amplitude, late stylolites can be vertical or exhibit different inclinations; they are related to tectonic stress and affected saddle dolomite, being cut by late fractures filled with calcite (Fig. 5.2b).

Although some stylolites may have developed in carbonates at burial depths of about 470m (Lind 1993), most probably formed at burial depths greater than 1000m. As stylolitization is a continuous process during diagenesis, it can be used only to separate early diagenesis from intermediate to deep burial diagenesis. Thus, dissolution and brecciation may have occurred at minimum burial depths of about 470m, to, more probably, depths of over 1.000m.

In Januária some vugs postdate sphalerite, the main stage of mineralization, and are filled with zinc silicate (Figure 5.3d) and white saddle dolomite. Some fractures also postdate sphalerite. These data indicate that the main dissolution events preceded and overlapped saddle dolomites. Fluid inclusions in rhombohedral SD indicated Th as high as 231°C, suggesting that dissolution was caused by heated (hydrothermal) subsurface fluids, at a time during burial, later than the inferred development of meteoric karst.

COMPARISONS WITH OTHER ORE DEPOSITS

Hydrothermal dissolution associated with saddle dolomite and ore minerals as described in Januária are common feature in epigenetic mineral deposits of MVT and Irish-Type.

In MVT mineral deposits, hydrothermal dissolution and saddle dolomite are linked and interpreted as being related to the same hydrothermal fluids. In the USA this association has been described by numerous authors, e.g. by Sverjensky (1981), Ohle (1985), Leach and Sangster (1993) Sangster (1995), among many others.

In the Silesian-Osark district, similar characteristics have been described by Saas-Gustkiewicz et al. (1982), Saas-Gutskiewicz (1996); Leach et al. (1996) among many others.

In the Western Canadian Sedimentary basin, hydrothermal dissolution associated with saddle dolomites is common (e.g. Aulsted and Spencer 1985; Morrow et al. 1986; Qing and Mountjoy 1989; Mountjoy and Halim Dihardja 1991; Qing 1991; Qing and Mountjoy 1994a,b; Mountjoy et al. 1999; Mountjoy et al. 2001; Reimer et al. 2001). Its products host not only important sulfide deposits as at the Pine Point District (Qing and Mountjoy 1994a), but also petroleum and gas deposits as well.

In Ireland, important Zn-Pb, in some cases Ag-rich, deposits are hosted in replacement dolostones affected by hydrothermal dissolution with associated saddle dolomite (Hitzman and Beaty 1996; Gregg *et al.* 2001). Dolostones and ore mineral are closely associated in the Navan area suggesting that dolomitization and mineralization were temporally and genetically linked;

dolomitization is interpreted to have played an important role in the hostrock preparation for ore emplacement.

Table 7.4. Comparison of most important characteristic of Januária Zn/Ag mineral deposits with those of MVT and Irish-Type

Selected features	**MVT**	**Irish-Type**	**Januária**
Occurrence in shallow marine carbonates / permeable units	Y	Y	Y
Location in weakly disturbed strata	Y		Y
Associatin with extensive dissolution and collapse breccias	Y	Y	Y
Close to ancient subaerial exposure surface	Y		Y
Presence of mineralized internal sediments	Y		Internal sediments (VfCD) are common, but fragments of ore mineral were not found
Coarsely crystalline dolomitization of host rock	Y	Y	Y
Presence of saddle dolomite (hydrothermal)	Y	Y	Y
Deposits are epigenetic and stratabound	Y	Y	Y
Association with faults or fractures	Y	Y	Normal faults are of regional importance; mineralization occurs mostly close to fault zones (most of them defined by photointerpretation)..

Thus, base-metal mineral deposits hosted in dolostones affected by hydrothermal dissolution in association with saddle dolomite, as described in Januária, is common worldwide, inspite of different ages of mineralization in MVT or Irish-Type deposits, they are all epigenetic.

Units of contrasting permeability and unconformities always exert an important control on the distribution of dolomitization and consequently on the mineral deposit emplacement.

Hydrothermal dissolution and subaerial exposure can produce somewhat similar solution vugs and breccias. For properly interpreting solution events associated with secondary dolomitization, it is crucial to stablish the timing and overall distribution of of dissolution events and avoid the common pratice of relating the solution events to the nearest unconformity.

7.4 SUMMARY AND CONCLUSIONS

There is no evidence of an extensive meteoric karst in the Januária region; dissolution features related to subaerial exposure in lithofacies afected by dissolution/collapse breccia are minor and found only at the top of the stromatolitic barrier. Occurrences of large-scale dissolution features are closely associated with saddle dolomite and sulfide/silicate ore minerals that indicate warm (presumably hydrothermal) fluids.

Dissolution features resulting from subaerial exposure strongly contrast with several aspects of subsurface dissolution with features like:

a) small vugs usually one or two centimeters across, whereas dissolution vugs hosting mineralization at Januária varies from centimeters to few a meters;

b) vugs at the top of the stromatolitic reef barrier are filled with McCD withouth mineralization, while dissolution vugs related to hydrothermal activity are commonly filled with late-stage SD, VfCD, sulfide/silicate zinc minerals, LCC and bitumen.

Petrographic evidences indicated that the dissolution and brecciation post-date early stylolites and, therefore, must have occurred during burial. At Januária, the main dissolution event postdates and overlaps saddle dolomite cementation. In addition, later dissolution cavities filled with late calcite postdate the mineralizing event, indicating that dissolution overlaps mineralization. Thus, dissolution occurs prior to and after saddle dolomite and was caused by subsurface hydrothermal fluids.

Meteoric karst has been inferred to be responsible for extensive dissolution and brecciation in many MVT districts and also in Irish-Type mineral deposits worldwide. In many cases there is no direct evidence to support a meteoric origin extensive dissolution and the timing of dissolution is often not constrained. The result of this study has important implications for other similar mineral districts in the middle São Francisco valley region where evidence for meteoric karst needs to be critically re-examinated. In cases like Januária, the influence of subaerial exposure has been overemphasized whereas the role of later hydrothermal dissolution, on the contrary, has been overlooked until now.

At Januária, dolostones and dissolution/collapse breccias that host mineral deposits are concluded to have been related to warm hydrothermal fluids acting over a large region during burial of the carbonate sediments. Homogeneization temperature in rhonbohedral SD from the Januária mineral deposits reached 231^0C (preliminary data) and in LCC are in the order of 108^0C to 189^0C, higher than those determined from most MVT deposits but comparable with Irish-Tipe mineral deposits. Consequently the mineral deposits as described above are epigenetic and share most of the characteristics of MVT and Irish-Type.

In Januária, as well as in most compable mineral deposits, impermeable or less permeable units acted as aquitards within the stratigraphic succession and provided important controls on the channeling and migration of ore fluids.

The impermeable units acted as aquitards restricting the vertical extent of the replacement dolomitized interval (~ 20m) and consequently the later distribution of dissolution/collapse breccias and mineralization emplacement. Both the lowermost unit, consisting of nonporous fine sediments of the dolomitic calcarenite member 3 and the lowermost unit (7A) of the dolomudstone member 7 acted as aquitards.

The identification of the main fault systems that possibly acted as conduits requires more detailed mapping, especially in the stable area of the basin, as in the middle São Francisco Valley region and is a worthy research project for the future.

CHAPTER 8

TIMING OF MINERALIZATION AT JANUÁRIA AS INFERRED FROM DIAGENESIS OF HOST DOLOMITES

Determining the timing of the mineralization at Januária is very difficult because of the lack of regional and local geochronological and paleomagnetic data. Several questions arise regarding dolomitization and mineral deposits in Januária. Among them are:

a) when did the large-scale hydrologic system, that played a key role in the mineralization and dolomitization along preferred conduit systems, start to operate in the São Francisco Basin?

b) what were the driving forces responsible for the migration of basin fluids/brines along this conduit system?

c) when did the ore metal emplacement occur?

These are basic questions for which at present there are no definite answers because of the paucity of critical data. However, several important clues are noted and discussed below.

General timing constraints

Rock paragenesis: petrographic studies indicate that saddle dolomites and locally cut across the dolomudstone/ooid-intraclast dolostone members and is later than early stylolites (Chapter 5). Thus, dolomitization occurred after deposition of the dolomudstone member, during burial but before anhedral dolomite.

As noter earlier, features that cross cut stylolites means they formed at depths greather than 500 to 600 m or more for limestones, and correspondingly deeper (perhaps >1000 m) for dolomites due to their greater resistance to pressure solution. Thus replacement dolomites had to have buried to moderate depths when they replaced limestones.

Since mineralization is closely associated with rhombohedral saddle dolomite, as discussed in the section of diagenetic paragenesis (Chapter 6), the timing of the formation of rhombohedral saddle dolomite provides some constraints that limit the timing of the mineralization. Mineralization postdates replacement dolomites and saddle rhombohedral dolomite. Thus emplacement of the ore minerals definitively happened during burial of the sediments and mineral deposits are epigenetic.

Sr isotopes: Sr isotopic data obtained in this research clearly indicate that deposition of the Sete Lagoas Formation took place about 590 to 600Ma, after the Marinoan glaciation represented by the sediments of the Jequitaí Formation. The Bambuí Group sediments represent a platform cover deposited over the são Francisco Craton, which was affected along its borders by the Brasiliano Orogeny (700 to 530Ma). The Januária region is located on the stable part of the basin, far from the Brasília and Araçuaí fold belts (Figure 2.2), and therefore not directly affected by the Brasiliano Orogeny. However growth faults systems was active in the region following deposition of the Sete Lagoas sediments (see Chapter 2)

Paleomagnetics: The São Francisco Sedimentary Basin, in which the Bambuí Group was deposited, has important and widespread carbonate units indicating development in low latitudes, that is confirmed by paleomagnetic data (D'Agrella et al. 1997).

Hypotheses genetically linking MVT and Irish-Type deposits to compressional tectonic events operating at some distance away from the mineral deposits are common in the literature (e.g. Oliver 1986, Leach and Rowan, 1986; Bethke et al. 1991; Hitzmann and Beaty 1996; Leach et al. 2001). However, there are exceptions, where mineralization is related also to fault reactivation during extensional deformation (e.g. Dorling et al. 1996; Leach et al. 2001), e.g. Nanisivik (Canada) and Lennard Shelf (Australia).

The Januária mineral deposits are discussed briefly in the context of the compressional and extensional deformation.

Compressional tectonics

The compressional tectonic model also known as squeegee model has been widely accepted by several authors (e.g, Oliver 1968; Garven and Freeze 1984; Bethke and Marshak 1990; Leach et al. 2001)

According to Leach et al. (2001), the genesis of MVT ores and global-scale tectonic events are intimately related. Lead-zinc ores would be formed mainly during large compressional tectonic events at certain times in the Earth's history. Despite some exceptions, the authors consider "that migration of MVT ore fluids is not a natural consequence of basin evolution; MVT districts instead formed mainly where platform carbonates had some hydrological connection to orogenic belts". There would be also a connection between paleoclimate and the formation of some MVT deposits as suggested by the dominance of evaporated seawater in fluid inclusions in MVT ores. "Paleoclimatic conditions that lead to the formation of evaporite conditions but yet have adequate precipitation to form large hydrological systems are most commonly present in low latitudes" (ibid). Evaporative conditions do not mean aridity and massive deposition of evaporite minerals. Low latitudes have been the prefered place for carbonate platform development.

Compressional tectonics occurred during the Brasiliano orogeny and could have been responsible for topography-driven dluid-flow (Figure 8.1,2). The main fault systems, in association with basin discontinuities and permeable strata, may have acted as conduits for fluids expelled from the adjacent orogenic belts into the more stable updip part of the basin. These tectonically expelled fluids would have played an important role in the diagenesis of the sediments in terms of dolomitization, ore deposition and probably hydrocarbon migration as well.

Presently it is not possible to determine whether or not mineral deposits are related to the compressional events of the Brasiliano Orogeny. However, if we consider the hypothesis that the Brasiliano Orogeny was the responsible for the topography driven flow (compression tectonic squeegee model), the timing of dolomitization and ore emplacement would be limited to the extent of the Brasiliano orogenic cycle. Consequently mineral deposits would be of Neoproterozoic age, but younger than 590 to 600Ma, the minimum age of carbonate sedimentation of the Sete Lagoas carbonate sedimentation (Bambuí Group).

Extensional tectonics

A second possibility is that the Januária Zn/Ag mineralization might be related to extensional deformation. In the geologically similar carbonate Lennard Shelf of the Devonian of Western Australia, shallow synsedimentary faults and adjacent carbonate rocks are the principal hosts of MVT base-metal deposits. The model involves overpressuring and episodic discharge of compaction-driven basinal brines during fault reactivation associated, in this case, with extensional deformation.

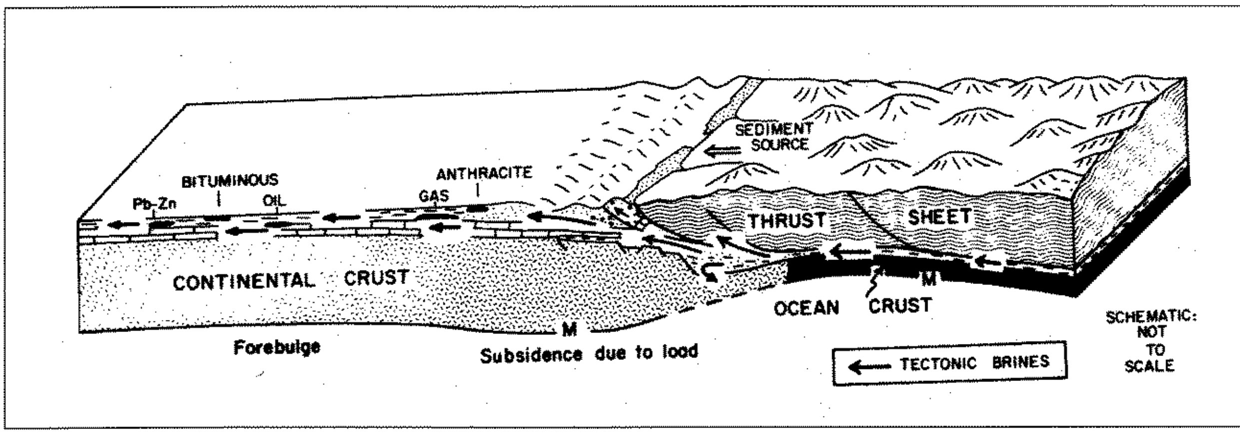


Figure 8.1. Block diagram of orogen when thrust sheets overrides margin sediments. Fluid flow tectonic brines are expelled from buried sediments (arrows) and injected into adjacent continent via conduit systems. These fluids may play an important role in the diagenesis of the sedimentary basin in terms of dolomitization, as well as hydrocarbon migration. Pb-Zn mineral deposits are located far from the orogenic belt. (from Oliver 1986).

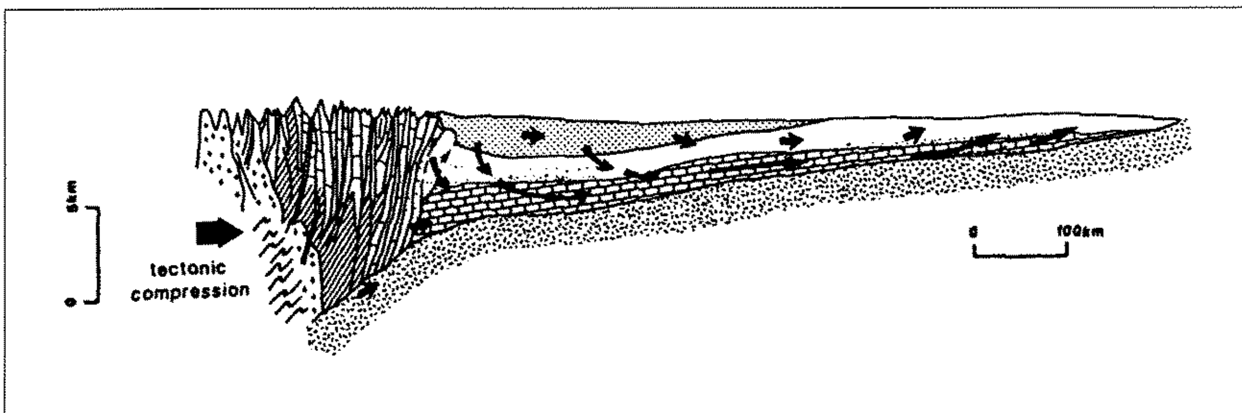


Figure 8.2. Conceptual model of topographically driven fluid flow in sedimentary basins: a compressional model (from Garven and Freeze 1984; Garven 1989).

As already discussed, Januária is located almost in the middle of the cratonic area, at least 250km away from any of the fold belts surrounding the craton. The region has been tectonically active for a long time, with blocks subsiding differently resulting in contrasting thickness of sedimentary deposits, locally exhibiting synsedimentary folds. Thus, tectonics exerted an important control on subsidence and facies distribution (see Fig. 2.3) indicating that normal, extensional fault systems played an important role in the evolution of the basin in that area.

Interestingly, the region is still tectonically active, with an earthquake reported in 1990 at Manga, 200km northeast of Januária (Ussami 1993).

However, as for the compressional model, there is insufficient data to determine whether the large-scale migration of basin brines in the Januária region were related to extensional deformation. If mineralization was be related to extensional deformation, the timing of the mineralization could be as young as somewhere in the Phanerozoic.

SUMMARY AND CONCLUSIONS

Zn-Ag mineral deposits of Januária are epigenetic, resulting from large-scale migration of warm, presumably hydrothermal fluids along preferential fault controlled conduit systems in the sedimentary basin that affected the Bambuí sediments during burial.

The age of the mineral deposits is doubtful, as is the driving mechanisms for fluid movement, which could be a compressive/tectonic one, related to the Brasiliano Orogeny, or one related to extensional faulting. If related to the Brasiliano orogenic cycle, mineralization would be Neoproterozoic in age; if related to an extensional event, it could younger and conceivably of Phanerozoic age.

Despite difficulties in establishing the driving forces for fluid flow and the timing of mineralization, the presence of an extensive hydrothermal system is clearly documented and defined for the middle São Francisco valley region. The migration of warm fluids using fault systems, unconformities and porous units of the basin as conduits occurred during burial of the lithified sediments of the Sete Lagoas Formation. This large-scale movement of tectonically expelled hydrothermal fluids played an important role in the diagenesis of the sedimentary succession in terms of dolomitization and ore deposition in the study area.

CHAPTER 9

SUMMARY AND CONCLUSIONS

9.1 GEOLOGIC SETTING AND SEDIMENTOLOGY OF THE SETE LAGOAS FORMATION

The Bambuí Group is a Neoproterozoic platform cover deposited on the São Francisco Craton, bordered by fold belts of the Brasiliano Cycle (700-530Ma) that affected deposition of Bambuí sediments, especially in the Brasília and Araçuaí fold belts. Far from the fold belts, in the stable area of the craton, normal faulting caused vertical displacement of basement blocks.

The Bambuí Group belongs to the São Francisco Supergroup and comprises the following formations: the basal Sete Lagoas (limestones and dolostones), Serra de Santa Helena (pelitic with lenses of limestones), Lagoa do Jacaré (limestones) and Serra da Saudade (pelitic with lenses of limestones), that altogether make up the Paraopeba Subgroup. Capping the subgroup, is the Três Marias Formation with immature siliciclastic sediments that ended Bambuí sedimentation.

The sediments of the Bambuí Group were subaerially exposed and eroded during the Paleozoic and part of the Mesozoic. They were unconformably overlain, during the Cretaceous, by the terrigenous sediments of the Urucuia Formation.

The age of the Bambuí Group is constrained by $^{87}Sr/^{86}Sr$ data on limestones to be around 590 to 600Ma.

In the middle São Francisco valley region the sedimentary pattern is closely related to differential tectonic subsidence related to NNE-SSW and NNW-SSE fault systems. Two main sedimentary domains are recognized relative to the São Francisco valley: the eastern domain that subsided much more (Bambuí sediments are ~700m thick) than the western one, made up of blocks that subsided differentially (thickness ranging from 50 to ~350m).

The Sete Lagoas sediments in the middle São Francisco valley are interpreted to represent an extensive carbonate platform affected by growth-faults active during sedimentation. The Januária region had a lower subsidence rate compared to the neighbouring areas (see Chapter 2).

Antecedent basement topography also influenced sedimentation. Thickness of the sedimentary succession thins to southwest reflecting shallower depositional environments and less accomodation space.

The Sete Lagoas Formation is informally divided into 7 members grouped into three main shallowing-upwards successions, basal, intermediate and upper successions.

The basal succession consists of two members 1 and 2; a thin, basal layer of pink dolomudstones lying over rocks belonging to the crystalline basement and described in the neighbouring areas does not outcrop in the study area.

The intermediate succession includes the interval between members 3 to the lowermost unit of the member 7 (unit 7A), and the upper succession is made up of the upper unit of the member 7 (unit 7B).

In the basal shallowing-upwards succession, argillaceous lime mudstone of low-energy subtidal to intertidal environment decreases upwards whereas calcirudite become frequent. Calcirudites are mainly rudstones and interpreted as storm deposition in tidal channels or intraformational sheet-like breccias in intertidal to supratidal flats. Detrital interbeds displaying low-angle cross-lamination are storm related. Tepee-like structures as desiccation crack layers suggest subaerial exposure. The basal shallowing-upwards succession is interpreted as recording a prograding interval deposited on a low-energy carbonate platform or a shallow shelf, where tidal flats were cut by tidal channels, affected by storms and intermittently exposed. This lowermost shallowing-upwards cycle probably records, at least in the study area, the first transgression at the start of Bambuí sedimentation.

The boundary between the basal and intermediate succession (between members 2 and 3) records a major increase in muddy layers displaying planar-parallel bedding interbedded with HCS; desiccation features are lacking. Overall these changes indicate a shift from a shallow, intermittently emergent environment (member 2 in basal succession) to a deeper low-energy setting in member 3 below fairweather wave-base.

Upwards in the member 3 sediments become sandier and consists of poorly preserved ooids and intraclasts, HCS/SCS are ubiquitous and there is no record of fairweather sedimentation. The depositional environment of the sandier unit is matter of controversy, because sandbodies are mostly considered as developed in shoreface, and its position in offshore would be related to a sea-level raise, but an offshore environment could also be sandier in high-energy shelfs. For the moment, the sandier unit of member 3 is interpreted as representing offshore sedimentation under stormy condition.

The pronounced change upwards, from units displaying HCS/SCS (member 3) to low-angle planar cross-bedding with interbeds of rippled bedding indicate a change in the environment, from a stormy period to a fairweather sedimentation. Changes in the physical conditions also indicate deepening waters that could be related to a sea-level rise affecting the member 3. The dolostone member 4 is interpreted as representing extensive submarine sandbodies developed in shoreface, on a "shelf or platform margin", periodically affected by storms.

Colonization of the sandbodies by microbial communities resulted in the development of the stromatolite biohers (member5) that reached the sea level, being intermittently exposed. They represent a reefal barrier developed close to or at the "shelf margin break". Stromatolite barrier reefs isolate different types of shelf lagoon in back reef depending on whether the stromatolitic rim was continuous or not. Barrier islands and/or shoals also could be responsible for low-energy environments along the shoreline.

The dolostone and stromatolite dolostone members (4 and 5) are interpreted as developed during a sea level highstand.

Stratigraphically above, the ooid-intraclst dolostone member 6 contains remains of trough, bidirectional and low-angle planar cross-bedding, commonly associated with beach environment but also to barrier islands systems and tidal channels. Sediments are ooidal and similar to those observed in the dolostone member 4; in addition, coarser intraclasts mixed with ooids show evidence of beachrock cementation; intraclasts with truncated grains are interpreted as beachrock slabs resulting from storm action. The presence of a restricted, lagoonal environment is indicated by the occurrence of packstones to wackestones. Coarser sand units lacking sedimentary structures and laterally limited are interpreted as tidal inlets. Eolian sediments were not identified.

The ooid-intraclast member 6 records a prograding phase in the carbonate platform development that is overlain by low-energy tidal flats (lowermost unit of the member 7), as accomodation space of the lagoons and tidal flats was filled.

The contact between the ooid-intraclast dolostone member 6 and the lowermost unit (7A) of the dolomudstone members 7 is either sharp or transitional and records environmental changes from inferred low-energy beaches to prograding tidal flats. Gradation occurs where tidal flat prograde over lagoonal sediments and sharp contacts where fine sediments covered sandier foreshore units. The presence of abundant oolitic interbeds restricted to the unit 7A, immediately above the ooid-intraclast dolostone member 6, indicates continuity of the sedimentation between member 6 and the lowermost unit (7A) of the member 7.

The lowermost unit (7A) of the dolomudstone member 7 records shallow subtidal to supratidal sedimentation with pronounced desiccation features on the top, and represents tidal flat progradation followed by subaerial exposure of the carbonate platform that ended the intermediate shallowing-upwards succession.

The upper unit (7B) of the dolomudstone member 7 form the uppermost shallowing-upwards succession and records low-energy peritidal carbonate successions few meters thick. Commonly these successions start with a basal, transgressive lag that is overlain by shallow subtidal fine sediments with thin dolomite intraclast horizons; stromatolite biostromes are also present and may diplay discrete desiccation features; these intervals are interpreted as representing shallow subtidal to intertidal environments. Small tepees, rare mud cracks and vugs containing geopetal features define the top of the small shallowing-upwards cycles that are overlain by transgressive sediments of the next sedimentary succession.

The uppermost succession is thus interpreted as representing a series of prograding tidal flat successions that record low-energy environments from shallow subtidal to high intertidal/supratidal.

The increase in pelitic sediments upwards in the overlying Serra de Santa Helena Formation shut down the carbonate platform.

The three main succession altogether are interpreted to be a parasequence set of a progradational stacking patterns, where sediments of each parasequence become successively shallower and more proximal upwards in the succession.

9.2 DIAGENETIC PARAGENESIS

The carbonate rocks of Sete Lagoas Formation at Januária has undergone diagenetic alteration in subaerial, submarine and subsurface environments. Diagenetic features of subaerial diagenesis include desiccation cracks, tepees, microstalactitic and meniscus cement and minor small-scale dissolution vugs. The diagenetic feature representing submarine environment is isopachous fibrous cement around allochems and suggests beachrock cementation.

Subsurface diagenesis resulted in the most important modifications in the Januária carbonate rocks, and includes: blocky sparry calcite cement, compaction and stylolitization, hydrothermal dissolution, dolomitization, sulfide and silicate ore minerals, late-stage coarse-crystalline calcite, elemental sulphur, fluorite, silica and bitumen

9.3 DOLOMITIZATION

Twelve types of dolomites are found in Januária region, among replacement dolomites (early and late) and cements. In paragenetic sequence, the main dolomites are: microcrystalline (McCD), medium-crystalline (MCD), coarse-crystalline (CCD), very-coarse crystalline (VcCD), saddle (SD) and very finely crystalline (VfCD).

McCD represent penecontemporaneous replacement dolomites and MCD/CCD, late replacement dolomites. VcCD, SD and VfCD are dolomite cements.

MICROCRYSTALLINE DOLOMITE

1) McCD occurs in peritidal sediments of the dolomudstone member 7; affects also stromatolite buildups and fine sediments of the stromatolite dolostone member.

2) The heaviest $\delta^{18}O$ value of McCD is -4.63‰, wich is within the range of calculated $\delta^{18}O$ values (-4.63 to –5.42‰) for dolomites that would precipitated from Neoproterozoic (Sete Lagoas Formation) seawater or slighly modified seawater.

3) The $^{87}Sr/^{86}Sr$ ratios of McCD range from 0.7085 to 0.7094, slightly higher than the estimated $^{87}Sr/^{86}S$ ratio of the Neoproterozoic (Sete Lagoas Formation) seawater, suggesting that their original isotopic signature were partly modified by later diagenetic fluids.

McCD probably formed contemporaneously at or just below the seafloor by Neoproterozoic seawater or slightly modified seawater, being later partly affected by diagenetic fluids as indicated by its $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratios.

MEDIUM and COARSE CRYSTALLINE DOLOMITE

1) MCD and CCD are widespread occurring in the dolostone and ooid-intraclast dolostone members (members 4 and 6, respectively).
2) The heaviest $\delta^{18}O$ value are of –6.94‰, slightly depleted compared with the estimated $\delta^{18}O$ signature of Neoproterozoic seawater. However, the $\delta^{18}O$ values of most MCD and CCD fall between –7.45 to –7.66‰ and are more depleted, although not strongly, than the estimated $\delta^{18}O$ signature of Neoproterozoic Sete Lagoas seawater.
3) The $^{87}Sr/^{86}Sr$ ratios of MCD and CCD are 0.7112 and 0.7118, and are more radiogenic than the estimated Neoproterozoic seawater of the Sete Lagoas Formation.

The data from the present study place constraints but do not provide an unequivocal conclusion, concerning the origin of MCD and CCD. Among several possibilities MCD and CCD could represent late diagenetic neomorphism over previous dolomite affected by migrating Sr-rich fluids at slightly elevated temperatures during burial. Another possibility is that MCD and CCD formed under burial conditions by Sr-rich fluids.

MCD and CCD postdate early stylolites suggesting that dolomitization occurred during burial.

VERY COARSE-CRYSTALLINE DOLOMITE and SADDLE DOLOMITE

VcCD and SD are closely associated with each other and occur in cavities and fractures in MCD and CCD.

1) VcCD and rhombohedral SD are commonly observed in the ooid-intraclast dolostone member 6 and lowermost unit (7A) of the dolomudstone members 7, extending across the limit of those members what indicate they were formed later than the hypothetical meteoric karst surface.

2) VcCD represents dolomite cement that overprinted earlier relacement dolomites. Rhombohedral SD fills vugs and fractures in prior dolomites. Rhombohedral SD and VcCD are very common in and around mineralized areas but VcCD can also affects coarse-grained sediments in barren areas SD poor.

4) VcCD and SD show similar $\delta^{18}O$ values which ranges from –8.40 to –9.62‰; these are the most depleted values.

5) The $^{87}Sr/^{86}Sr$ ratios of VcCD (with subordinate SD) in MCD or CCD are similar to the host dolomite, thus more radiogenic than the estimated Neoproterozoic seawater.

VcCD and rhombohedral SD are interpreted as being formed in the subsurface during burial by warm diagenetic fluids of similar chemical composition. White SD with symmetrical saddle forms is iron-rich and later than rhombohedral SD.

VERY FINELY CRYSTALLINE DOLOMITE

1) VfCD is restricted to dissolution/collapse breccia layer and affects all the above described dolomites, including rhombohedral SD.
2) Act as cement and internal sediment filling cavities of different sizes; may exhibit normal grading; VfCD cements all kinds of breccia fragments made up of McCD, MCD, CCD, VcCD and SD.
3) VfCD is, in some areas, closely related to ore mineral emplacement. In mineralized areas cavities with VfCD are bigger than in barren areas and may represent caves.

4) The heaviest $\delta^{18}O$ values is of -4.48‰, whichis within the range of calculated $\delta^{18}O$ values (-4.63 to 5.42‰) for dolomites that would have precipitated from estimated Neoproterozoic seawater of Sete Lagoas Formation.
5) The $^{87}Sr/^{86}Sr$ ratios of VfCD ranges from 0.7113 to 0.7105, more radiogenic than the estimated Neoproterozoic seawater and similar to those of MCD, CCD and VcCD.

Although VfCD exhibit $\delta^{18}O$ values similar to those estimated for the Neoproterozoic seawater of the Sete Lagoas Formation, the Sr isotopic composition is not compatible with the estimated seawater. Also there is no diagenetic feature or field relationship could suggest formation of VfCD directly from seawater.

VfCD is very similar to the named "sanded dolomite" deposited as internal sediment in cavities related to hydrothermal activity. VfCD also cements all kinds of clasts derived from wall cavities, including fragments of the dolomudstones, stratigraphically above the supposed meteoric karst surface.

VfCD is here interpreted as resulting from chemical or chemically induced mechanical disaggregation of dolomite by warm brines. Supporting the hypothesis of action of warm, possible hydrothermal brines, Hoefs (1993) interprets heavy $\delta^{18}O$ values of restricted isotopic composition, as obtained in VfCD, as resulting from action of brines of high salinity and of high temperature. Salinity of MVT and Irish-Type fluids are typically 10-30wt% and can be developed trough evaporites, incorporation of formation brines or infiltration of evaporative surface waters.

Fluid inclusion data from late-calcite and fluorite indicate deposition from warm fluids with temperatures above $100^{0}C$; these diagenetic phases are later than VfCD and ore mineral emplacement. The presence of oil inclusions in sphalerite and late-stage calcite also argues for processes operating during burial.

9.4 ORIGIN OF DISSOLUTION VUGS AND BRECCIAS

Meteoric karst has been inferred to be responsible for extensive solution and brecciation in the Januária region as well in the São Francisco valley. In many cases there is no direct evidence to support a meteoric origin for the solutions and the timing of dissolution is no sufficiently well constrained. This study indicated that dissolution related to subaerial exposure differs from subsurface dissolution in at least three aspects:

1) dissolution vugs related to meteoric waters are small (few centimeters), and observed on the top of a stromatolite reef barrier while vugs hosting mineralization are much larger, from centimeter to decimeter in size (could be bigger, prior to exploitation);
2) the infilling material of vugs related to subaerial exposure is only fine dolomitized sediment. Dissolution vugs in mineralized areas are commonly filled with saddle dolomite, VfCD, sulfide, late-stage calcite cements, fluorite and bitumen;
3) dissolution features related to a meteoric karst would occur only below the top of the ooid-intraclast dolostone member 6 while later-stage vugs and breccias with SD affect the lowemost part of the unit 7A (dolomudstone member 7), stratigraphically above.

Therefore, meteoric waters caused only minor dissolution although could have enhanced porosity and permeability and provided conduits for late hydrothermal fluids. However most of the vugs and breccias were produced by hydrothermal fluids during burial. These results imply that epigenetic ore deposits are not always related to an unconformity. Mineralization can occur in any available vugs and/or fractures whatever their origin. Also, the evidence of meteoric karst for other MVT districts should be critically re-examined. In Januária region, the influence of subaerial exposure has been over-emphasized and later extensive hydrothermal dissolution of carbonates overlooked. The ore-bearing dissolution/collapse breccias are interpreted to be the result from selective sulfide replacement of pre-ore collapse breccia.

9.5 TIMING OF MINERALIZATION

One of the unsolved problems is the age of mineralization, which can only be constrained within broad limits. As SD is closely associated and overlaps with mineralization at Januária, the time of dolomitization places some additional constraints on the timing of mineralization. As dolomitization occurred after the deposition of the dolomudstone member 7, during burial, the emplacement of ore minerals also took place during burial of the sediments.

Considering the compressional model, the Januária mineral deposit could be related to the evolution of the Brasiliano Cycle and thus restricted to the Neoproterozoic – between 590 to 600 and 530 Ma.

However if emplacement of the Januária Zn/Ag mineral deposits is related to extension, deformation, the timing of mineralization need not be restricted to the Neoproterozoic and could be Phanerozoic in age.

9.6 METALLOGENIC CONTROLS OF THE MINERAL DEPOSITS

The main control in epigenetic base metal ore deposits in carbonate rocks without magmatic affiliation is ground (host rock) preparation related to tectonics. Tectonics can provide the driving forces responsible for fluid flow over large, semicontinental areas (Oliver 1986). Faults and fractures are the main conduits for the ascending fluid flow in a basin. Within the basin, fluid flow is controlled not only by tectonics but also by porosity and permeability of sedimentary units of great importance as conduits for the fluid flow. Permeable units act as aquifers allowing fluid flow in contrast to impermeable or less permeable units retarding or blocking fluid circulation. Thus the interaction of faults with permeable sedimentary units and unconformities in the basin define the regional pattern of related dolomitization and dissolution/collapse breccia development. This same association, depending on the availability of the sulphur, also controls ore emplacement.

Fluid flow is recurrent in sedimentary basins and fluids are of different composition resulting in dissolution with vugs and cavities as well as the formation of open space brecciation caused by dissolution/collapse. This often occurs prior to base metal emplacement. Brecciation is recurrent and widespread.

Zn/Ag mineral deposit of Januária as well as mineralization in the middle São Francisco valley are inferred to be related to a subaerial exposure with meteoric karst by most authors, except Robertson (1963). Mineralization is here interpreted to be epigenetic, having similarities with MVT but also Irish-Type mineral deposits. It is also considered as hydrothermal, based on the fact that:

1. Brecciation and dissolution occur continuously across the members 6 and 7, crosscutting the hypothetical unconformity developed above the member 6.

2 Diagnostic meteoric karst features such as caves, speleothems, vadose cements and terra rossa (Esteban and Klappa 1983; James and Choquette 1990) are not found in the dissolution/collapse breccia layers.

3 The angular shapes of some breccia fragments cemented by rhombohedral SD indicate they formed after lithification.

4 There is absence of extensive dissolution and/or brecciation in the limestones, even in the partly dolomitized ones (member 3), below the dolomitized/brecciated level.

5 Dissolution and brecciation postdate stylolites and late dolomite replacement.

6 The dissolution/collapse breccia hosting sulfide minerals result from several stages of brecciation and dissolution.

7 δ^{18} O values in VcCD and SD are the lighest δ^{18}O values in dolomites studied, and are interpreted as forming from high temperature migrating fluids during burial (Morrow 1990; Allan and Wiggins 1993), and formed from other dolomitizing fluids that differed from those responsible for replacement dolomites generation.

8 Results of fluid inclusion analysis suggest that dissolution of replacement dolomites and cementation of rhombohedral SD occurred under high temperatures (at least 231^{0}C), by action of warm fluids, during burial.

Thus, late subsurface events better explain the large-scale dissolution features, dolomitization and mineralization that occur in the ooid-intraclast dolostone and dolomudstone members (6 and 7). It is recognized that the lack of data related to thermal maturation of organic matter (vitrinite reflectance) and about the regional geothermal gradient of correlated stratigraphyc units located far from areas affected by dissolution/collapse brecciation and mineralization, impose constraints in this conclusion. However, the sum of available data allows us, as already proposed by Robertson (1963), to consider the mineralization as hydrothermal.

The driving force responsible for the overall fluid flow in the region is not known; the compressional tectonic related to Brasiliano Orogeny or the extensional tectonic related to regional normal faults could be responsible for starting the fluid flow into the basin. NNE-SSE and NNW-SSE regional fault systems certainly acted as conduit for dolomitizing and mineralizing fluids as seen by an increase in mineral deposits in the vicinities of Serra do Cantinho Hill next to the faults and fractures (see Figures 1.3 and 4.1). Determining the mechanisms responsible is beyond the scope of this research.

Fluid flow in the carbonate sedimentary rocks of the Bambuí Group in the middle São Francisco valley was at least partly controlled by units of contrasting permeabilities. Although local subaerial exposure affected the top of basal stromatolite bioherms (stromatolite member 5) and the uppermost part of the unit 7A of the dolomudstone member 7, features indicating extensive meteoric karst were not observed. Thus the first major metallogenic control related to carbonate sediments was the regional distribution of strata with contrasting permeabilities. The lowermost unit to act as an aquitard in the Januária region was the basal fine carbonate of the dolomitic calcarenite member 3 and the uppermost unit was lithologies of the dolomudstone member 7. These aquitards controlled dolomitization, dissolution/ collapse breccia and ore mineral deposits.

Dolomitization is a requirement for mineral deposit emplacement as well as the presence of dissolution/collapse breccia cemented by saddle dolomite. Dissolution/collapse breccia cemented by SD are found on the lowemost part of the dolomudstone member 7 but are more develloped in the ooid-intraclast dolostone member 6 stratigraphically bellow. Dolomudstones acted as an aquitard and ascending fluids couldn't flow up, spreading laterally and generating regional dissolution/collapse breccia cemented by saddle dolomite. The local availability of sulphur defines the emplacement of ore mineral in specific areas.

It is interesting to note that important dissolution/collapse breccia body that could represent caves developed over coarse sediment of ooid-intraclast dolostone member 6, interpreted as representing paleochannels. Dissolution/brecciation affected replacement dolostones as well as rhombohedral SD, and open spaces are filled with VfCD; some of these brecia bodies are mineralized.

Thus, metallogenic controls related to basin evolution in the study area are porous and permeable sedimentary units, related or not to an unconformity, and interlayered between impermeable units. During burial these permeable units act as conduits for warm, possible hydrothermal dolomitizing and mineralizing fluids.

9.7 CLOSING REMARKS

1 – This study suggests that diagenetic features such hydrothermal dissolution, dolomitization and mineralization in the São Francisco Basin are genetically linked to tectonics affecting the basin. Compressional or extensional tectonics creates hydrodynamic systems that initiate large-scale fluid flow played a key role in dolomitization and mineralization along preferencial conduit systems. The main conduits within the basin were faults/fractures as well as permeable units of the stratigraphic succession. Permeable strata have acted as aquifers controlling the migration of the fluids throughout the basin sealed by impermeable units had acted as aquitards.

The widespread hydrothermal activity with associated mineral deposits is of utmost importance indicating, in such cases, the diagenetic features must be systematically studied across the basin, especially where dolomitization and disolution/collapse breccia are present.

These conclusions are of great importance for mineral exploration offering new possibilities of mineral deposits in the large area hydrothermally affected.

2– The age of the Bambuí Group has been matter of controversy, the absence of described paleontological record making difficult age definition of the group and comparison with other carbonate sedimentary basins.

The $^{87}Sr/^{86}Sr$ data obtained from selected limestones withouth important diagenetic imprints (this study) define the hypothetical Sr isotopic composition of the seawater during deposition of the Sete Lagoas Formation; the estimated isotopic composition can be used as a reference for diagenetic studies. These data also confirm sedimentation of the Bambuí Group starting at around 590 to 600Ma, as already defined by others authors.

Comparing our results with data from Shields (1999), it becomes clear that the Bambuí Group is younger than supposed and the Jequitaí Glaciation (Jequitaí Formation) can be correlated with the Marinoan Glaciation (Figure 9.1). This is a basic data allowing comparison of the Bambuí Group with other carbonate basins worldwide.

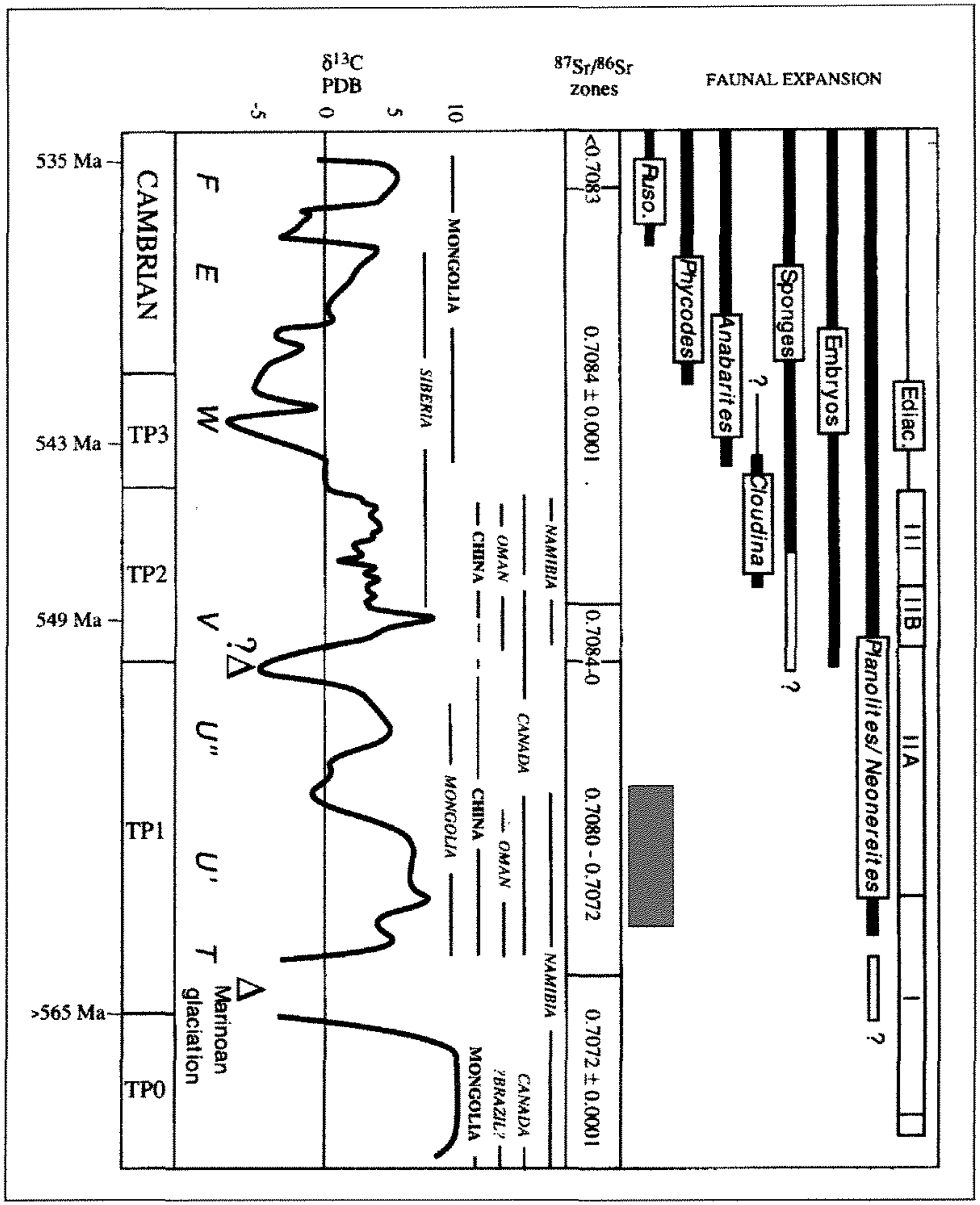


Figure 9.1. Seawater Sr isotope composition of the Sete Lagoas Formation (*red*) shows that the Bambuí Group is younger than supposed, and allows correlation between the Jequitaí and Marinoan glaciation (Shields 1999).

9.8 CONSIDERAÇÕES FINAIS

O Grupo Bambuí constitui uma cobertura de plataforma neoproterozóica depositada sobre o Craton do São Francisco, o qual se apresenta rodeado por faixas de dobramentos marginais relacionadas ao Ciclo Brasiliano (700-530Ma) que afetaram a deposição dos sedimentos Bambuí, especialmente ao longo das faixas Brasília e Araçuaí. Em áreas distantes das faixas de dobramentos, na porção estável do cráton, falhas normais provocaram deslocamento vertical de blocos do embasamento. O Grupo Bambuí é parte do Supergrupo São Francisco, sendo composto pelas formações Sete Lagoas (basal), Serra de Santa Helena, Lagoa do Jacaré e Serra da Saudade, as quais perfazem o Subgrupo Paraopeba. A Formação Três Marias é a unidade de topo do grupo. Os sedimentos do Grupo Bambuí foram expostos, erodidos durante o Paleozóico e parte do Mesozóico, e recobertos por sedimentos cretácicos da Formação Urucuia.

Na região do médio São Francisco, o padrão de sedimentação é estreitamente relacionada à subsidência tectonica diferencial relacionada aos sistemas de falhas NNE-SSW e NNW-SSE. Dois principais domínios sedimentares são reconhecidos em relação ao rio São Francisco: o domínio leste, que apresentou maior subsidencia que o domínio oeste.

A Formação Sete Lagoas, objeto desta pesquisa foi informalmente dividida em 7 membros, agrupados em 3 principais ciclos de sedimentação, denominados basal, intermediário e superior.

O ciclo basal é constituído pelos membros calcilutitos argilosos (basal) e calciruditos (1 e 2, respectivamente); é interpretado como representando um intervalo regressivo cujos sedimentos foram depositados numa plataforma carbonática de baixa energia, cortada por canais de maré e esporadicamente afetada por tempestades.

A sucessão intermediária é composta pelos membros calcarenito dolomítico (3), dolomito (4), stromatolito dolomítico (5) e dolomito oolítico/intraclástico (6) e pela unidade inferior (7A) do membro 7, dololutito. A interpretação geral desse ciclo é que ele representa uma sucessão regressiva após uma transgressão ocorrida quando da deposição do membro 3, em *offshore*, passando por depósitos de *shoreface* com barreira recifal estromatolítica, ambiente lagunar, praias e planícies de marés. O ciclo intermediário termina com a exposição subaérea da plataforma carbonática. Evidencias que sugerissem uma possível discontinuidade resultante de exposição subaérea ocorrida sobre o membro 6, não foram encontradas.

A sucessão superior é composta por pequenos ciclos regressivos de planícies de marés, que no conjunto formam uma sucessão progradante desenvolvida em ambientes de baixa energia.

As três sucessões principais são consideradas como compondo um *set* regressivo de parasseqüências.

Os sedimentos pelíticos da Formação Serra de Santa Helena encerraram a sedimentação carbonática da Formação Sete Lagoas.

Os carbonatos estudados apresentam feições de alterações diagenéticas características de ambientes subaéreo, submarino e de subsuperfície. Feições diagenéticas desenvolvidas em ambientes subaéreos estão representadas por *tepees*, gretas de ressecação, cimentação vadosa e pequenas cavidades relacionadas à dissolução meteórica. Feição diagenética indicativa de ambiente submarino é representada por cimento isópaco acicular ao redor de aloquímicos e interpretada como representando cimentação do tipo *beachrock*.

Feições diagenéticas de subsuperfície são predominantes e incluem, entre outras, compactação, cimentação por calcita espática, dissolução hidrotermal, dolomitização, sulfetos e silicato de Zn, calcita espática de cristalinidade grossa (LCC), fluorita e betumem.

Os depósitos minerais estão hospedados em dolomitos formados por dolomitos de substituição (precoce e tardia) e cimentos dolomíticos, os quais foram intensamente afetados por dissolução/colapso, gerando brechas.

Doze tipos de dolomitos foram identificados em Januária, nem todos relacionados aos depósitos minerais. Em seqüência paragenética, os mais importantes são os dolomitos microcristalinos de substituição precoce (McCD), os dolomitos de substituição tardia representados pelos dolomitos de cristalinidade média (MCD) e grossa (CCD), dolomita de cristalinidade muito grossa (VcCD), saddle dolomita (SD) e dolomita de cristalinidade muito fina (VfCD). VcCD, SD e VfCD são cimentos.

Quanto à distribuição espacial, McCD afeta sedimentos do membro 7, estromatólitos e sedimentos finos associados (membro 5); MCD e CCD são abundantes e afetam litologias dos membros 4 e 6. VcCD e SD ocorrem intimamente associadas e embora sejam mais abundantes no membro 6, são comuns também no membro 7, cortando a suposta superfície de exposição subaérea que teria ocorrido sobre litologias do membro 6; são portanto posteriores à deposição dos sedimentos carbonáticos do membro 7. SD ocorre nas formas romboédrica, mais comum, e precoce em relação à forma simétrica, que é de cor branca leitosa. VfCD é restrita a zonas de brechas de dissolução/ colapso e é tardia em relação às outras dolomitas, exceto possivelmente à SD de côr branca.

Os diversos tipos de dolomitas e os calcários basais foram analisados para isótopos estáveis e também para Sr. Amostras selecionadas de calcários que apresentam o mínimo de alteração diagenética, e não contém argilo-minerais, foram analisadas para C/O e $^{87}Sr/^{86}Sr$. Os resultados obtidos são considerados como representando a provável composição isotópica da água do mar quando da deposição dos sedimentos da Formação Sete Lagoas, e foram utilizados como referência para avaliar as variações isotópicas nas outras fases diagenéticas analisadas.

Os resultados isotópicos de Sr permitem ainda estimar a idade de deposição da Formação Sete Lagoas, considerada como tendo se iniciado em torno de 590 a 600Ma.

Os valores considerados como representando a água do mar Neoproterozóico à época da deposição da Formação Sete Lagoas estão, com relação ao $\delta^{18}O$ (PDB), situados entre –6.11 e –6.56‰ (média = -6.39), e os valores de $\delta^{13}C$ variam entre 0.26 e 0.58‰ PDB (média = 0,42‰). A relação $^{87}Sr/^{86}Sr$ da água do mar nesse mesmo oceano apresenta valores situados entre 0.7076 e 0.7079.

Os valores obtidos nas diferentes fases diagenéticas analisadas serão discutidos a seguir:

-McCD: os valores de $\delta^{18}O$ permitem considera-los como tendo se formado a partir da água do mar, à época da deposição da Formação Sete Lagoas, ou água do mar ligeiramente modificada. A relação $^{87}Sr/^{86}Sr$ obtida é ligeiramente superior à definida para a água do oceano Neoproterozóico da Formação Sete Lagoas, o que sugere modificações da composição original por fluidos diageneticamente tardios.

-MCD/CCD: os valores obtidos de de $\delta^{18}O$ são ligeiramente depletados em relação à presumível composição isotópica da água do mar e os valores de $^{87}Sr/^{86}Sr$ são enriquecidos em relação à água do mar. A pequena diferença isotópica observada em relação ao δ^{18O} padrão não permite conclusões definitivas sobre a formação desses dolomitos; entre as possibilidades estão o neomorfismo de dolomitos preexistentes tardiamente neomorfizados e afetados por fluidos ricos em Sr, ou formação durante soterramento a partir de fluidos enriquecidos em Sr. Os cristais de dolomita cortam estilólitos, indicando formação em subsuperfície.

-VcCD e SD romboédrica apresentam valores semelhantes e muito depletados em $\delta^{18}O$ em relação aos demais dolomitos. Os valores de $^{87}Sr/^{86}Sr$ são semelhantes aos obtidos para MCD/CCD. Inclusões fluidas em SD sugerem temperatura de formação acima de 230^{0}C. Por essas razões VcCD e SD são interpretadas como tendo se formado em subsuperfície, durante soterramento, por fluidos diagenéticos quentes e de composição semelhante.

-VfCD cimenta fragmentos de dolomitos de substituição e SD romboédrica, mas ocorre também como sedimento detrítico, apresentando laminação e às vezes gradação normal. Os valores de $\delta^{18}O$ são anômalos em relação aos outros cimentos e mais próximos da presumível composição isotópica da água do mar, mas não os valores de $^{87}Sr/^{86}Sr$, que são enriquecidos. Também não existem feições de campo ou diagenéticas que sugiram formação diretamente a partir da água do mar. Por essas razões VfCD é interpretado como resultando de desagregação química ou quimicamente induzida por fluidos quentes (*warm brines*) em subsuperfície. VfCD é muito semelhante aos denominados "dolomitos arenosos" depositados em cavernas e relacionados à atividade hidrotermal em outros depósitos minerais, como por exemplo os que ocorrem na região de Ozark, na Polônia.

Todas os dolomitos descritos ocorrem no nível de dolomito brechado que hospeda as mineralizações, o que sugere que dolomitização, dissolução e brechação ocorreram em subsuperfície, tardiamente, durante o soterramento dos carbonatos. Cavidades resultantes de dissolução meteórica são poucas, pequenas e preenchidas apenas com sedimento fino dolomitizado; as cavidades resultantes de dissolução e colapso que ocorrem no nível brechado são preenchidas pelas fases dolomíticas descritas e também por sulfetos, LCC, fluorita e betumem, entre outros. Conseqüentemente, as principais feições de dissolução são consideradas como tendo se desenvolvido em subsuperfície, a partir de fluidos quentes, não guardando qualquer relação com possíveis descontinuidades da bacia.

As brechas mineralizadas são interpretadas como resultantes da ação seletiva de fluidos mineralizantes sobre um nível de brecha preexistente, em subsuperfície, o que permite concluir que a mineralização é epigenética e hidrotermal.

A época de colocação das mineralizações é um problema a ser resolvido. Se estiver relacionada à compressão ocorrida no Ciclo Brasiliano, a idade das mineralizações estará compreendida entre 590-600Ma e 530Ma, sendo portanto neoproterozóica. Caso esteja relacionada à tectonica distensiva que atuou na região, a mineralização pode ser inclusive fanerozóica.

Os controles metalogenéticos, estão relacionados em primeira instância a fatores tectônicos e estruturais, que não fazem parte dos objetivos desta pesquisa.

No âmbito da bacia sedimentar, os principais controles metalogenéticos são unidades porosas e permeáveis que atuaram como conduto para as soluções dolomitizantes e mineralizantes; as unidades permeáveis são limitadas por fácies impermeáveis, que impedem ou dificultam a circulação dos fluidos (aquitardes). Na região em estudo, os níveis porosos ocorrem especialmente no membro 6 e parte do membro 4, os mais afetados por dissolução e colapso, compondo o extenso nível regional de brechas; a parte inferior do membro 7, dololutito, também se encontra brechada e participa do nível regional mineralizado. Unidades que limitaram a circulação dos fluidos e atuaram como selantes são as unidades que compõem a parte superior, não brechada do membro 7, e na porção inferior da sucessão sedimentar, as unidades lamosas do membro 3. Unidades de granulação mais grossa são afetados de modo mais intenso por dissolução e colapso gerando brechas cujas cavidades são frequentemente prenchidas por VfCD e sulfetos de Zn/Ag.

Durante o soterramento, as unidades permeáveis atuaram como condutos para fluidos aquecidos responsáveis pela dolomitização, brechação e mineralização.

Assim, este estudo sugere que a movimentação de fluidos diagenéticos tardios que atuaram na região de Januária está genéticamente ligada à tectonica que afetou a bacia sedimentar. O tectonismo gerou um extenso sistema hidrodinâmico, que se movendo através de condutos preferenciais promoveu a migração em larga escala de fluidos, os quais tiveram um papel fundamental nos processos de dolomitização, dissolução hidrotermal e mineralização. Os estratos permeáveis da bacia atuaram como aqüíferos, controlando a migração desses fluidos.

A extensa atividade hidrotermal à qual estão relacionados os depósitos minerais é extremamente importante e sugere que as rochas carbonáticas devem ser estudados também sob o aspecto diagenético em toda a bacia, mas em especial onde dolomitização e brechas de dissolução e colapso estão presentes.

Estas conclusões são de grande importância para a exploração mineral pois abrem novas perspectivas em termos de depósitos minerais, uma vez que a atividade hidrotermal comumente afeta extensas regiões.

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