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DIAGENETIC MINERALIZATION OF THE JURAMENTO  
SEDIMENT-HOSTED STRATIFORM Cu-(Ag) DEPOSIT,  
SALTA DISTRICT, NORTHWESTERN ARGENTINA

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Ce memoire intitulé:

DIAGENETIC MINERALIZATION OF THE JURAMENTO  
SEDIMENT-HOSTED STRATIFORM Cu-(Ag) DEPOSIT.  
SALTA DISTRICT, NORTHWESTERN ARGENTINA

présenté par: DURIEUX Carlos Gustavo

en vue de l'obtention du diplôme de: Maîtrise ès sciences appliquées

a été dûment accepté par le jury d'examen constitué de:

M. DARLING Richard, Ph.D., président

M. BROWN Alex C., Ph.D., membre et directeur de recherche

M. CHARTRAND Francis, Ph.D., membre

## DEDICATION

Con todo mi cariño para...

... Ana, Lucia y Emilia.

... mis padres, hermanos y hermanas.

... mis nonitos.

... Ana.

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## RÉSUMÉ

Cette étude confirme les caractéristiques de gîte de cuivre-(argent) stratiforme en milieu sédimentaire du gisement de Juramento. Ce dernier est localisé au nord-ouest de l'Argentine dans la province de Salta. Le gisement a été évalué pour son potentiel économique par la compagnie Paramount Ventures and Finances Inc. L'estimation actuelle de ses réserves fait état de 11 Mt à 0,83 % de cuivre et 19,2 g/t d'argent.

Ce travail décrit les environnements syn-sédimentaires de dépôt des roches hôtes de la minéralisation et leur diagenèse au cours de l'enfouissement. L'environnement de syn-diagenèse est celui des cycles de diminution de profondeur sur une plateforme carbonatée à faible pente. La plateforme présente des caractéristiques plutôt lacustres que marines. Les évaporites sont peu nombreuses mais évidentes en formes des nodules et des cristaux isolés de gypse-anhydrite et en forme des pseudomorphes dans les carbonates de la Formation Yacoraite inférieure. Les roches hôtes étaient riches en matière organique et elles contiennent également d'abondantes pyrites syndiagénétiques disséminées. Ces pyrites résultent de la réduction biogénique des sulfates.

Pendant la diagenèse précoce, il a eu une augmentation de la porosité, causée par la dissolution des carbonates. Ceci a complété la préparation des roches hôtes pour l'introduction et le dépôt des métaux. Le fluide minéralisateur serait une saumure riche en chlorures, créé à basse température et dans des conditions oxydantes. Capable de transporter le cuivre, le plomb, le zinc et l'argent, ce fluide proviendrait des couches rouges continentales sous-jacentes du Pirgua. Les métaux auraient été déposés avant la silicification et la fermeture de la porosité des sédiments de la Formation Yacoraite lors de leur enfouissement. La minéralisation (chalcocite, bornite, chalcoppyrite, tennantite-tetraédrite, galène et sphalérite) a été déposée par le remplacement de la pyrite syndiagénétique et/ou du gypse. Les métaux et leurs sulfures présentent la distribution

suivante: les sulfures riches en cuivre et argent sont concentrés près de la base de la Formation Yacoraite alors que les sulfures riches en plomb et zinc apparaissent progressivement plus haut dans les strates de cette formation.

L'évènement de la minéralisation est clairement postérieur à la plupart des évènements de la syndiagenese et antérieur à la silicification et l'enfouissement, ceci est typique des gîtes stratiformes de cuivre en milieu sédimentaire.

Dans le cas de la pyrite, les isotopes du soufre sont aussi typiques d'un fractionnement biogénique: en ce qui concerne les sulfures des métaux de base, ils présentent des valeurs plus proches de zéro et auraient pu être dérivés des sulfates présents (gypse) ou apportés par l'influx minéralisateur. La réduction inorganique des sulfates est peu probable en raison du manque d'évidences des processus de haute température et le manque d'efficacité des mécanismes de réduction biogéniques sous environnement syndiagenetique. Une source de soufre réduit provenant d'un gaz est peut probable compte tenu de la dispersion des valeurs isotopiques.

## ABSTRACT

This study documents the sediment-hosted stratiform copper characteristics of the Juramento copper-silver deposit located in the Salta Province, northwestern Argentina. The deposit has been evaluated for its economic potential by Paramount Ventures and Finances Inc. and current estimates of its reserves are 11 Mt @ 0.83 % Cu and 19 g/t Ag.

Our research considered firstly the environments of synsedimentary host-rock deposition and its burial diagenesis. The diagenetic environment is that of shallowing-upward sequences on a low-gradient ramp platform, probably lacustrine rather than marine. Evaporites are rare but evident in nodules and single crystals of gypsum-anhydrite and their pseudomorphs in the lower Yacoraite carbonates. This host-rock was rich in organic matter and contains abundant disseminated syndiagenetic pyrite resulting from biogenic sulphate reduction.

Early diagenesis produced increased porosity by dissolution of primary carbonate which completed the ground preparation for subsequent base-metal introduction and deposition. The ore-forming fluid would have been a low-temperature oxidized chloride-rich brine carrying copper, lead, zinc and silver, and originating in the underlying Pirgua continental redbed unit. The metals were deposited before silicification and subsequent closure of the Yacoraite porosity by deep burial. The ore minerals (chalcocite, bornite, chalcopyrite, tennantite-tetrahedrite, galena and sphalerite) were precipitated by replacement of syndiagenetic pyrite and gypsum. The ore metals and their sulphides were zoned with copper-(silver)-rich sulphides more proximal to the basal Yacoraite unit and lead and zinc located progressively higher in the Yacoraite strata.

The timing of ore-metal emplacement was clearly after the majority of the syn- and early diagenetic features and before silicification and advanced burial diagenesis, which is typical of most sediment-hosted stratiform copper deposits.

Sulphur isotopic data is also typical of syndiagenetic biogenic fractionation for pyrite; however, ore sulphides are heavier and could derive from in-situ sulphates (gypsum) or an influx of sulphate with the ore fluids. Reduction of sulphate is unlikely because of the lack of evidence for high-temperature inorganic reduction and lack of efficient biogenic reduction below the syndiagenetic burial. A sour gas source of sulphide is unlikely because of the variable isotopic values.

## CONDENSÉ EN FRANÇAIS

Ce travail concerne l'étude de la nature et de la genèse du gîte de cuivre-(argent) stratiforme en milieu sédimentaire de Juramento. Le gisement est situé dans la Province de Salta, ~60 km au sud est de la ville de Salta et près de la rivière du même nom. Il a été évalué pour son potentiel économique par la compagnie Paramount Venture and Finances Inc. L'estimation des réserves fait état de 11 Mt à 0,83% de cuivre et de 19,2 g/t d'argent.

Du point de vue géomorphologique, le gîte de Juramento est situé dans le domaine de la chaîne subandine, l'unité géomorphologique la plus à l'est des Andes centrales. Cette division est la conséquence d'une série d'événements tectoniques qui a affecté la région: ces événements s'étalent depuis le Précambrien jusqu'à nos jours.

Pendant le cycle Brasiliano, 700-800 Ma, des structures profondes ont influencé l'emplacement des nombreux bassins jusqu'à l'époque du Tertiaire. Ces structures sont conjuguées et ont des directions NE/SW (le linéament de l'Aconquija) et NW/SE (le linéament Olacapato-El Toro). Pendant le Paléozoïque (cycle Hercynien) se sont développés deux autres méga structures qui ont aussi joué un rôle important dans l'évolution tectonosédimentaire de la région: la faille de la Puna et la faille Ocloyica qui ont une direction générale N-S. Ces structures constituent l'actuelle division entre la Puna de la Cordillère Orientale et de la chaîne subandine.

Le cycle Hercynien débute au Cambro-Ordovicien avec la formation d'un bassin ouvert vers l'ouest, la faille de la Puna fonctionne alors avec un jeu normal. Pendant l'Ordovicien tardif, il y a eu la phase orogénique Ocloyica caractérisée par la compression et l'inversion du bassin, par l'activation des failles pré-existantes et par la formation de nouvelles structures tel que la faille Ocloyica. Par la suite, on observe un

relâchement des contraintes et la formation des petits bassins à l'ouest de la faille de la Puna et à l'est de la faille Ocloyica. Le cycle Hercynien se termine au Devonien supérieur-Carbonifère par l'orogénèse Chañica.

Pendant le Mésozoïque commence le cycle andin qui dure jusqu'à présent et qui est responsable de la division géomorphologique actuelle. D'abord au Crétacé, il y a une période d'extension et de formation d'un rift qui s'étend depuis le nord-ouest de l'Argentine jusqu'au Pérou. Dans le nord-ouest de l'Argentine, le rift s'est développé le long des grandes structures pré-existantes qui ont servi de limite à ce nouveau bassin (Bassin de Salta). L'ensemble des failles délimite également des sous-bassins avec un haut structural nommé la dorsale de Salta-Jujuy. Puis au Tertiaire commence la période de compression et de formation de la chaîne des Andes (les phases Inca, Quechua et Diaguita). Lors de la compression, les éléments structuraux mentionnés précédemment ont joué pour accommoder les nouvelles contraintes tectoniques.

Les sédiments hôtes de la minéralisation de Juramento se sont déposés principalement pendant le Crétacé et correspondent aux sédiments du Groupe Salta. Deux périodes de sédimentation sont reconnus: synrift et postrift. Pendant la période synrift se sont déposés les sédiments correspondant au Sous-groupe Pirgua (Neocomien-Campanien), composé des formations La Yesera, Las Curtiembres et Los Blanquitos. Les trois formations étaient déposées dans un milieu continental et sous un climat aride donnant un dépôt de couches rouges.

Pendant la période postrift se sont déposés les sous-groupes Balbuena et Santa Barbara. Le Sous-groupe Balbuena est constitué par trois formations: Lecho, Yacoraite et Tunal. Ces formations contrastent fortement avec les formations du Sous-groupe Pirgua par leur milieu de sédimentation subaérienne et par leur nature carbonatée. La période de sédimentation postrift se termine par le dépôt de sédiments fins en milieu continental du

Sous-groupe Santa-Barbara. Le Sous-groupe est constitué par les formations Mealla, Maiz Gordo et Lumbrera, toutes déposées avant l'inversion tectonique du bassin.

À l'échelle de la zone étudiée (la propriété de Paramount Ventures and Finances Inc.), Juramento inclut deux crêtes aiguës de direction nord-sud (Cerro del Plomo et Cerro del Cobre), séparées par une petite vallée. Les deux crêtes se joignent au sud pour former une seule crête qui continue vers le sud. Cerro del Plomo et Cerro del Cobre, sont limitées par des failles majeures inverses de direction parallèle aux crêtes. De nombreuses failles mineures de direction ENE-ESE recoupent la zone étudiée et affectent l'attitude locale des couches.

Les sommets des deux crêtes sont occupés par la Formation Yacoraite, les flancs internes (vers la vallée) par la Formation Lecho et le fond de la vallée par les couches rouges de la Formation Los Blanquitos. Les flancs externes des crêtes sont constitués des sédiments de la Formation Tunal et Mealla. À l'ouest des deux crêtes, les sédiments de la Formation Los Blanquitos sont observés en contact avec des sédiments interprétés comme étant d'âge dévoniens, ces derniers constituent le socle du rift. La disposition générale et l'attitude de la stratification souligne la géométrie d'un pli anticlinal avec un axe plongeant vers le nord.

Les sédiments de la Formation Los Blanquitos (Sous-groupe Pirgüa) correspondent à des conglomérats de couleur rouge et à des grès composés de quartz, feldspaths potassiques, plagioclases, microcline, tourmalines et fragments de roches ignées. Les grains sont subanguleux à anguleux et leur ciment est hématitique. Ces sédiments ne présentent aucune trace d'altération hydrothermale.

La Formation Lecho (Sous-groupe Balbuena inférieur) est composée des grains de sable moyen à fin composés de quartz, feldspaths, microcline, tourmalines et mica blanc. Le

ciment est calcaire. On observe aussi des composantes allochimiques à l'intérieur desquelles se trouvent des agglomérations de pyrite. Cette formation est facilement repérable par sa couleur blanche-jaune pâle qui contraste avec celle des sédiments du Pirgua.

Les formations Los Blanquitos et Lecho sont surmontées par la Formation Yacoraite (Sous-groupe Balbuena moyen) où se trouve la majorité de la minéralisation cupro-argentifère. Quoique de nature essentiellement carbonatée, la Yacoraite présente des nombreux sous-types de roche: grainstones, packstones, wackestones et mudstones, siltstones, boundstones stromatolitiques et conglomérats intraformationnels qui sont importants pour l'interprétation des milieux sédimentaires de la roche-hôte de la minéralisation.

Les grainstones sont composés principalement d'oolites radiales ou concentriques avec un ciment équigranulaire de calcite. Sont également présents de nombreux fossiles tels que des ostracodes, des pellicipodes et des gastéropodes. Il est aussi possible d'observer des grainstones formés par des oncolites. Les grainstones et les packstones sont plus abondants et les bancs sont plus épais vers la base de la formation (Yacoraite inférieur). Les mudstones présentent des bioturbations et on y trouve des fossiles ainsi que des grains de pyrite (et d'autres sulfures où l'unité est minéralisée).

Les stromatolites sont composés de fines laminations calcaires assez uniformes qui occasionnellement alternent avec de fines laminations de silt. Ils forment des bancs de quelques centimètres d'épaisseur, surtout vers le milieu de la Formation (le Yacoraite moyen) et vers le sommet de cette formation. Les siltstones, également nombreux dans Yacoraite et surtout vers le sommet de la formation, sont composés des grains de quartz-feldspath et de mica blanc de la taille du silt grossier. Le pourcentage de ciment et de matrice carbonatée est important.

La Formation Yacoraite est surmontée par les sédiments de la Formation Tunal (Sous-groupe Balbuena supérieur). Il s'agit d'alternances de petits bancs de grainstones oolitiques et de sédiments détritiques à grain très fin. Cette formation diffère de la formation précédente par sa couleur verdâtre.

La séquence stratigraphique à Juramento se termine par La Formation Mealla, qui consiste essentiellement en siltstones et en pélites de couleur rouge à orange.

La minéralisation étant principalement contenue dans la formation Yacoraite, nous avons orienté nos recherches pétrologiques vers les minéraux et divers éléments présents dans les sédiments de cette formation. Notre but étant de déterminer les relations entre les différents processus qui sont responsables de la présence de ces minéraux et qui ont affecté ces sédiments. Ainsi nous avons observé les minéraux suivants: calcites, dolomites, quartz (sous différentes formes), pyrites, gypses, feldspaths, phosphates ainsi que des hydrocarbures.

La calcite est l'élément prépondérant dans les sédiments de Yacoraite. En utilisant des techniques de coloration, deux variétés ont été repérées: rose et mauve. La calcite se trouve sous forme de ciment, de matrice et comme constituant essentiel des différents éléments allochimiques.

Comme ciment, la calcite est présente sous forme de cristaux idiomorphes. Ces cristaux forment un ciment équigranulaire qui remplit les espaces interparticulaires, les porosités de type vadose ainsi que les ouvertures dans les fractures. Un autre ciment, calcitique et de type fibreux, est occasionnellement observé autour de certaines oolites.

Dans la matrice, la calcite est surtout présente sous forme de micrite comme support des éléments allochimiques. De la microsparite, aussi observés dans la matrice, est

interprétée comme le résultat de la recristallisation de la micrite. La calcite est le matériel de base des éléments allochimiques. Elle est présente dans les pelloïds, dans les lumps, dans les coquilles de fossiles et dans le cortex des oolites.

La dolomite est aussi très présente dans la Formation Yacoraite, surtout dans les sédiments à grains fins du Yacoraite moyen et supérieur. Elle remplace à différents degrés les sédiments calcaires jusqu'au point de former des dolomies. Elle est facilement détectable par la couleur blanchâtre qu'elle confère aux sédiments et aussi par les techniques de coloration. Il faut préciser que la minéralisation n'est pas limitée seulement aux sédiments dolomitisés.

Deux textures ont été identifiées pour la dolomite: l'une à grain fin et l'autre à grain grossier. La dolomite à grain grossier contient des pochettes de dolomite à grain fin et est donc interprétée comme le résultat de la recristallisation de celle à grain fin.

Il est important de noter que: 1) des fragments de siltstones dolomitisés sont retrouvés dans un conglomérat intraformationnel; 2) des rhomboédres de dolomite sont disséminés dans une matrice de silice; 3) des agrégats de pyrite incluent des éléments allochimiques (non ou peu dolomitisés) vers leurs centres; et 4) ces éléments allochimiques sont complètement dolomitisés vers les bordures (en s'éloignant des bordures des agrégats les éléments allochimiques sont dolomitisés et sont soutenus par un ciment de silice). Ces observations suggèrent une origine précoce de la dolomitisation, postérieure à la formation de la pyrite et antérieure à l'arrivée de la silice. Ces faits démontrent aussi que les sédiments dolomitisés furent affectés par des processus tardifs tel que l'enfouissement.

La silice se trouve sous deux formes: des grains détritiques de quartz et de la silice authigénique. Les grains détritiques de quartz sont présents dans l'ensemble de la

formation. La silice authigénique est également abondante; il s'agit d'une part de grains authigéniques de quartz qui occupent des espaces intergranulaires et des bordures autour des grains détritiques et d'autre part des agrégats équigranulaires et fibreux d'opale et de microquartz. Les agrégats, remplissant des espaces vides et remplaçant certains oolites et fossiles, ont aussi été observés remplaçant des cristaux ou des nodules de gypse.

La pyrite est aussi très abondante dans les sédiments de la Formation Yacoraite. Deux textures sont reconnues: la pyrite disséminée à grain très fin et la pyrite automorphe à grain grossier. La pyrite à grain très fin est trouvée dans les plans de litage, à l'intérieur des cortex des oolites, dans les laminations des stromatolites et en bordure des fantômes de fossiles micritisés. Des agrégats de pyrite à grain très fin forment une texture particulière dite framboïdale qui est interprétée comme le résultat de l'activité des bactéries réductrices de sulfates qui se nourrissent de matière organique. La pyrite à grain très fin est interprétée comme étant un minéral très précoce dans la diagenèse.

La pyrite à grain grossier est aussi abondante que la pyrite à grain très fin, mais elle se situe dans des espaces intragranulaires à la place des laminations et des éléments allochimiques. On a observé à plusieurs reprises des agrégats de pyrite à grain très fin qui ont tendance à être redistribués pour former de la pyrite à grain grossier. Donc, elle est interprétée comme étant formée plus tardivement, probablement pendant la compaction des sédiments ou la déformation du bassin.

Des grains de pyrite correspondants aux deux textures rencontrées ont été analysés pour leurs teneurs isotopiques en soufre. Les résultats montrent des valeurs légères, allant de -43 à -27‰, et typiques de la fractionation produite lors de la réduction des sulfates par des bactéries.

Le gypse, le seul sulphate identifié lors de notre étude, se trouve sous forme de nodules et de cristaux idiomorphes, sous forme de remplissages des fractures et comme ciment avec texture poeciloblastique. Les nodules et les cristaux idiomorphes de gypse se trouvent surtout dans la Formation Yacoraite supérieur. Communément, le gypse est remplacé par la silice, une texture précoce. On observe aussi des grains de chalcopryrite comme pseudomorphes lamellaires des cristaux de gypse où les lamelles de gypse représentent un ciment formé avant le remplissage final des pores. Cette texture est aussi interprétée comme une diagenèse précoce.

Le gypse situé dans les fractures est tardif car il remplit des fractures qui recoupent des structures sédimentaires et diagénétiques. Le gypse poeciloblastique qui occupe des cavités de dissolution (probablement produites pendant le période d'exposition récente des sédiments) est aussi interprété comme étant tardif.

Les hydrocarbures de la formation sont observés dans des fractures qui recoupent à la fois le ciment et les éléments allochimiques. Ils sont également présents dans les espaces intercrystallines du ciment équigranulaire. Les fractures sont tardives, probablement produites pendant la déformation associée à l'inversion du bassin. L'introduction des hydrocarbures est postérieure à cette fracturation.

Les feldspaths existent sous deux formes : les feldspaths détritiques et les feldspaths authigéniques. Les feldspaths d'origine détritique correspondent au feldspath potassique, au plagioclase et au microcline. Les feldspaths authigéniques se trouvent autour des grains détritiques de feldspaths potassiques.

La minéralisation présente dans la Formation Yacoraite est divisée en deux types : primaire et supergène. Les sulfures disséminés correspondant à la minéralisation primaire sont: la bornite, la chalcocite, la chalcopryrite, la galène, la sphalérite et la tennantite-tetrahedrite.

La sphalérite présente des textures de remplacement auprès de la pyrite là où elle est observée en contact avec cette dernière. Par contre, quand elle est observée en contact avec d'autres sulfures, la sphalérite est incluse dans ces sulfures qui forment des bordures ou anneaux.

La galène est plus souvent en contact avec la sphalérite et elle forme également des anneaux autour de celle-ci. Cette texture est interprétée comme une texture de remplacement.

La tennantite-tetrahedrite forme des anneaux autour de la galène et de la sphalérite: il s'agit encore une fois d'une texture de remplacement. La tennantite-tetrahedrite se situe aussi en bordure des grains de galène et de sphalérite. Ces textures sont interprétées comme un remplacement de l'ensemble des sulfures par la tennantite-tetrahedrite.

La chalcopryrite est souvent associée à la tennantite-tetrahedrite. La chalcopryrite montre aussi des textures de remplacement des cristaux de gypse.

La bornite forme des bordures autour des autres sulfures et sulfosels mentionnés précédemment et, quand elle est observée en contact avec la chalcocite, cette dernière se situe en bordure de la bornite.

Deux sortes de bornite ont été repérées : la bornite rose et la bornite mauve. La première est riche en fer et soufre et la deuxième est riche en cuivre. La bornite rose présente des textures d'exsolution de chalcopryrite, ces textures indiqueraient que la bornite rose s'est formée à basse température et que le réarrangement des éléments pour produire la chalcopryrite en exsolution s'est effectué lors du réchauffement durant l'enfouissement des sédiments.

Les observations précédentes indiquent que la sphalérite est le sulfure le plus précoce, suivie par la galène, ensuite les sulfosels et enfin les sulfures de cuivre. Les analyses des isotopes du soufre des sulfures indiquent que l'ensemble de la minéralisation possède des valeurs plus lourdes (-25 à -8‰) que la pyrite (-43 à -27‰).

À partir des observations faites sur les échantillons des carottes de forage, les sulfures et les sulfosels présentent une zonation verticale apparente des métaux. D'une façon générale, la chalcocite occupe le Yacoraite inférieur, parfois jusqu'à la transition au Yacoraite moyen. La bornite et la chalcopyrite se trouvent progressivement plus abondantes vers le sommet, avec la chalcopyrite surtout importante vers la transition entre le Yacoraite inférieur et le Yacoraite moyen, et parfois la transition entre le Yacoraite moyen et supérieur en association avec les sulfosels riches en argent. La galène se retrouve à partir du Yacoraite moyen jusqu'à la base du Yacoraite supérieur et elle se superpose à la zone supérieure où la sphalérite est dominante. Progressivement, l'abondance de la sphalérite décroît vers le sommet du Yacoraite supérieur et donne place à une zone dominée par la pyrite.

La minéralisation supergène est représentée par des oxydes de fer, des carbonates de cuivre, de plomb et de zinc, et des sulfures de cuivre. Les carbonates de cuivre sont la malachite et l'azurite et les sulfures sont la covellite et la digénite qui forment des bordures autour des grains de sulfures de cuivre primaires.

Nous pouvons récapituler le milieu de sédimentation et la diagenèse afin d'identifier le milieu et la séquence de mise en place de la minéralisation. Il est possible de classer les processus affectant les sédiments de Yacoraite en trois étapes de diagenèse: la syndiagenèse, la diagenèse précoce, la diagenèse tardive, et deux étapes postérieures: la surimposition des phénomènes tectoniques et l'altération supergène.

Tout d'abord il faut insister sur le fait que les sédiments carbonatés ont tendance à se concentrer vers la base de la Formation Yacoraite et les sédiments détritiques vers le sommet de la formation. Ensuite, ces sédiments se séparent en deux groupes : les sédiments de haute énergie et ceux de basse énergie. Ainsi, les grainstones et packstones sont des repères incontournables; en général, ces derniers sont suivis vers le bas par des sédiments carbonatés de basse énergie, tel que des wackestones, des mudstones et des sédiments détritiques très fins. Vers le sommet, on retrouve des stromatolites et des siltstones. Ces séquences ressemblent beaucoup à des séquences de diminution de profondeur identifiées pour des plateformes carbonatées de faible pente où la sédimentation se fait dans des conditions de moins en moins profondes. Les sédiments de faible énergie se seraient déposés sous forme de plateforme ouverte loin de l'action des vagues, tandis que les sédiments de haute énergie se seraient déposés plus près de la rive. Les sédiments détritiques terrigènes constituent des sédiments de zone de rivage.

Pendant la syndiagenèse, on a regroupé les phénomènes précoces qui ont pris place à l'interface eau-sédiments, tels les nodules et les cristaux de gypse automorphe qui déplacent les sédiments ainsi que les cristaux de gypse trouvés comme ciment dans certains grainstones remplacés par la suite par des sulfures. Des microorganismes ont affecté les sédiments comme en témoignent la micritisation. La pyritisation aussi a lieu très tôt, comme le démontrent la texture framboïdale probablement issue de l'importante activité organique anérobie. Le milieu de sédimentation a affecté les sédiments préexistants produisant la dissolution de certains fossiles et du ciment de vadose. On a aussi observé des restes de ciment fibreux, mais ce ciment ne semble pas avoir été très répandu. Une dolomitisation eut place aussi pendant cette étape.

L'étape de diagenèse précoce s'est produite entre quelques centimètres et quelques dizaines de mètres d'enfouissement. Les processus correspondants à cette étape sont le

tassement des sédiments non cimentés et le développement de fractures. Un ciment de calcite de vadose, qui ne remplit pas complètement les pores, s'est produit pendant cette étape. L'arrivée des métaux s'est aussi produite par la suite pour créer, par exemple, les pseudomorphes de cristaux de gypse non déformés remplacés par de la chalcopryrite. Ensuite, la silice entourent à la fois des grains de sulfures et de dolomite, suggérant que la minéralisation a lieu après la dolomitisation et avant l'apparition de la silice. La silice se serait déposée avant l'enfouissement avancé des sédiments comme le prouve les grains authigéniques de quartz pris entre deux oolites dont les contacts sont de pression et de dissolution. Il y a également des grains authigéniques de quartz qui sont inclus dans des stylolites, interprétés comme étant formés avant le développement de ces derniers.

La diagenèse tardive après l'enfouissement avancé des sédiments est surtout observée dans la compaction et la déformation des oolites, dans la recristallisation de la micrite et de la dolomite à grain très fin et dans le développement des stylolites. Les stylolites se sont développés après avoir atteint au moins 500 mètres de profondeur.

Pendant l'inversion du bassin, il y a eu lieu la fracturation des sédiments lithifiés, un ciment calcique passablement phréatique et l'introduction des hydrocarbures.

La dernière étape affectant les sédiments à Juramento est l'altération supergène pendant l'exposition récente des sédiments. C'est pendant cette dernière période que se sont développés une porosité par dissolution, un ciment de gypse poeciloblastique et les minéraux d'altération supergène.

Donc, les fluides porteurs de la minéralisation semblent avoir pénétrés par la partie inférieure de la formation, ils auraient été dérivés des couches rouges du Sous-groupe Pirgua où ils se seraient chargés de sels et métaux. Ils seraient rentrés dans la

Formation Yacoraite, qui a été préparé diagénétiquement pour piéger les métaux contenus dans ces fluides. La préparation diagénétique des sédiments de Yacoraite consiste principalement de la conservation d'une perméabilité moyenne et l'abondance de soufre en forme de gypse et pyrite syndiagénétique dans un sédiment réducteur. À mesure que les fluides ont progressé à travers les strates du Yacoraite, ils ont remplacé les sources de soufre réduit disponibles et déposé les métaux selon leurs mobilités ( $Zn > Pb > Cu$ ). À la base se concentrent les sulfures riches en cuivre et à mesure que l'on monte dans la stratigraphie on retrouve des sulfosels, des sulfures de plomb et finalement des sulfures de zinc. La minéralisation aurait été introduite tôt pendant la diagenèse alors que les sédiments étaient perméables et avant que les ciments remplissent et bouchent les pores. La température lors de la minéralisation n'aurait pas dépassé les 75°C. Les analyses des isotopes du soufre démontrent que le soufre de la minéralisation est plus lourd que celui de la pyrite, probablement à cause d'une contribution de soufre du gypse ainsi que de la pyrite.

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## LIST OF ABBREVIATIONS

CS: Core sample

DC: Drill core

DDH: Drill hole

FOV: Field of view - defined for the long dimension of photomicrographs.

HS: Hand sample

JDH: Juramento drill hole

PPL: Plane polarized light

PTS: Polished thin section

RL: Reflected light

TS: Thin section

XPL: Crossed polars

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## **CHAPTER 1**

### **INTRODUCTION**

This study concerns the nature and genesis of the Juramento sediment-hosted stratiform copper-silver prospect located in the Sub-Andean Range about 60 km directly southeast of the city of Salta (Salta Province) in northwestern Argentina (Fig. 1.1). At the regional scale, the host Yacoraite Formation is also mineralized in Jujuy Province and southern Bolivia to the north. As such, an investigation into the specific conditions of metal deposition at Juramento could have broad applications to exploration for similar occurrences of copper-silver mineralization throughout this extensive area of west-central South America. Although the geology of the entire Salta area was examined in parallel with recent detailed surface mapping and drilling at the Juramento property, the current report deals principally with the mineralization at Juramento.

Access to Juramento is readily made via approximately 110 km of mostly paved roads: take route 9 east from the city of Salta to connect with route 34, and continue on route 34 south to the Juramento River, then southwest on gravel roads to the Paramount Ventures and Finances Inc. property.

The topography in the area is moderate, including ridges striking north-south, at altitudes varying from 800 to 2800 m. Slopes are up to 35° in some cases.

The climate is semi-arid, with a rainy season from December to March. Vegetation at lower altitudes, typical of the Chaco-Parana basin, comprise abundant spinifex brushes,

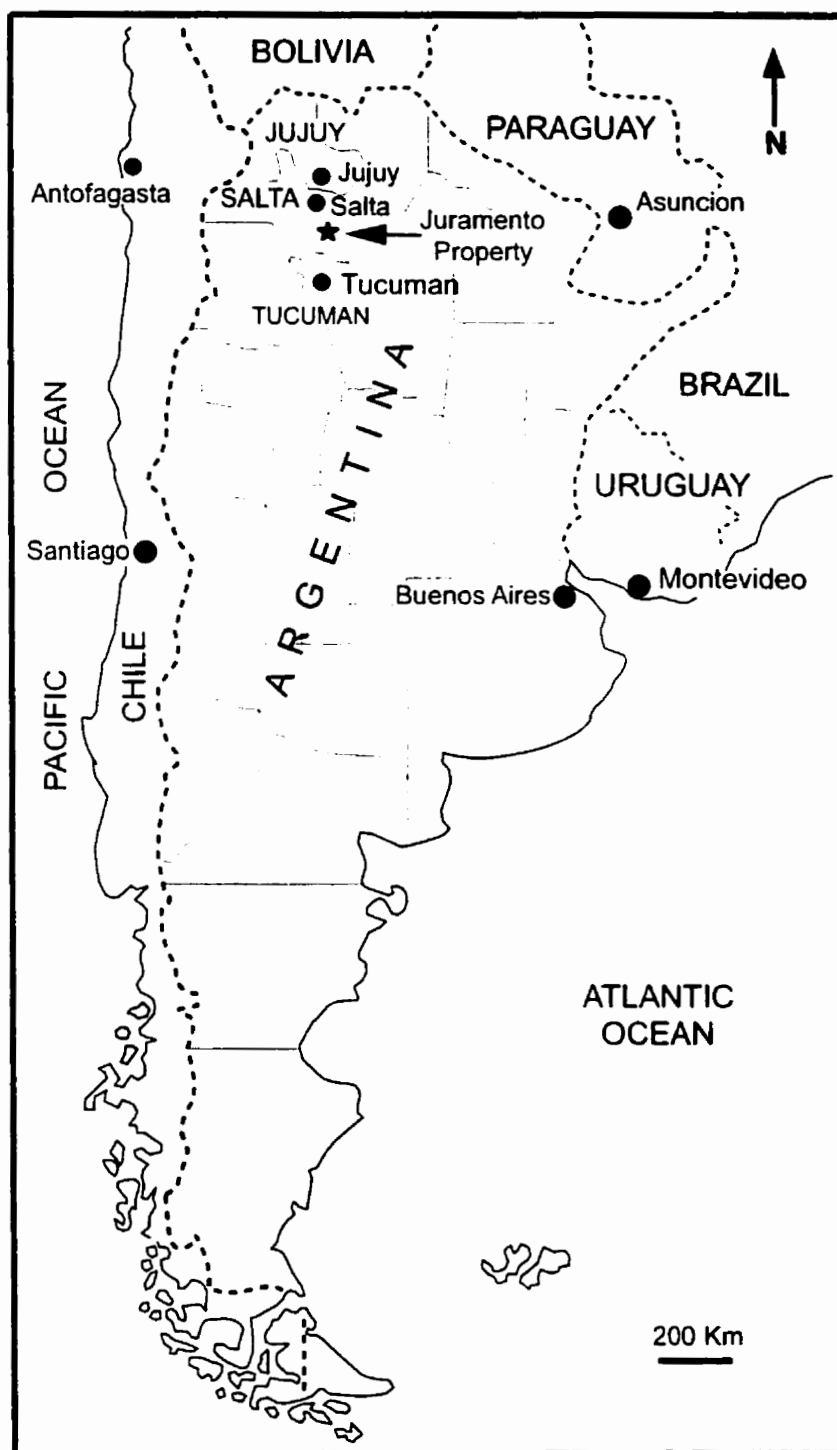


Fig. 1.1: Relative location of the Juramento property in northwestern Argentina, with the names of provinces of this portion of the country and their respective major cities.

sparse trees and cactus. Trees on ridge slopes and creek bottoms give way to high grass above 1500 m elevation.

Mining and prospecting in the area dates back over at least the last three centuries, with old workings and artisanal smelter ruins still visible today. Small-scale mining became sporadically active during the 1950s and 1960s, as well as in other areas of the provinces of Salta and Jujuy, because of the establishment of a smelter in the city of Jujuy (150 km north of Juramento). During this period, mining activity in the Juramento prospect area was concentrated on vein-type mineralization, especially chalcocite and secondary copper carbonates which form pervasive, highly visible, greenish stains on outcrops. The smelter closed in the early 1970s and all mining operations ceased immediately after.

Early descriptions of copper mineralization, similar to that of Juramento and at workings northeast of the prospect area, were given by Angelelli (1950, 1972) and Ruiz-Huidobro (1968). Both authors described the primary mineralization as hydrothermal veins formed from fluids ascending through fractures in limestones. They speculated that the mineralization was related to intermediate and basic volcanism because of the close temporal and spatial relationship of volcanic rocks to the mineralized host rocks.

In 1980, Pecomrio (a subsidiary of Rio Algom Ltd.) carried out exploration in the Juramento area, using a sediment-hosted stratiform copper deposit (SHSCD) model. Their report concluded that the mineralization was low temperature, stratabound and epigenetic, and that the original ore mineral was chalcocite (Pecomrio unpublished interim report, in Mason, 1996). Pecomrio estimated the resource potential at 9 million tonnes at 1% Cu and 20 g/t Ag based only on the Cerro del Cobre prospect, one of two mineralized ridges at Juramento.

Later studies by Espisúa et al. (1983) and Sureda et al. (1986) supported the interpretations of Pecomrio, especially concerning the classification of the mineralization and interpreted metallogenetic controls. However, these interpretations remained speculative because observations were limited to the supergene zone. Nevertheless, their work, summarized in Fontboté et al. (1990), recognized the stratabound character of the deposit. Surprisingly, their studies were omitted in Flint's (1990) review of sediment-hosted stratabound copper deposits of the Andes.

In 1995, Dr. Ian Mason, senior consulting geologist for Paramount, recognized the economic potential for this type of deposit and started work in this and other areas in northwestern Argentina that had similar geologic characteristics. His targets included several small- to medium-size deposits among the many showings that concurred with the sediment-hosted stratiform copper deposit model (Mason, 1996). Aside from the recognition of certain basic characteristic features of this deposit type, there was no clear evidence for the timing or conditions of emplacement of the mineralization. Also, the nature of primary mineralization at depth remained unknown. Information on these aspects would be invaluable "in determining the size and, to an extent, the grade of the deposits" (Mason, 1996) because sediment-hosted stratiform copper deposits mineralization is typically very extensive laterally along bedding and may reach grades of 1 to 4 or 5% Cu (Kirkham, 1989, 1997).

In March 1996, Dr. R. V. Kirkham of the Geological Survey of Canada visited Juramento and other Paramount properties in the area. He mentioned that the area has many characteristics common to sediment-hosted stratiform copper deposits mineralization and he agreed with the general genetic model applied by Mason (Kirkham, 1996).

In 1996-1997, Paramount drilled the Juramento property, obtaining twenty-five diamond

drill cores totaling 3114 m in length. The cores crosscut the stratigraphy of two mineralized ridges, Cerro del Plomo and Cerro del Cobre, and outlined a total indicated resource of 11 million tonnes with grades of 0.83% Cu and 19.2 g/t Ag (Rotzien, 1998).

In late 1996, the author was engaged to carry out mapping, especially on the Juramento property, and to conduct a masters-level research project on the metallogenic characteristics of the sediment-hosted stratiform copper deposits mineralization under the supervision of Professor Alex Brown at l'École Polytechnique de Montréal. Field work included a two-month period in 1996 and a three-month period in 1997. The present thesis summarizes the results obtained in the field and in follow-up laboratory analyses.

The aims of the study are:

- 1) to describe the primary copper mineralization,
- 2) to study relationships between the host rocks and the primary mineralization,
- 3) to identify mechanisms that controlled metal precipitation,
- 4) to provide a genetic model for the deposit based on observations made, and
- 5) to suggest applications of this model to exploration.

In addition to field mapping and drill core logging, to attain these objectives, a total of 117 samples were collected from 16 drill holes that intersect primary sulphide mineralization under the zone of supergene alteration; an additional eight samples were selected from surface exposures. Four polished sections and 121 polished thin sections were made for petrographic and mineragraphic studies of the host rocks and mineralization. A modified version of the Dickson (1965) staining technique was used to distinguish between dolomite and calcite, and to observe variations in their Fe and Mg contents (see also Hitzman, 1999). In addition, 12 samples of pyrite and cupriferous sulphides were selected for sulphur isotope analysis.

The results are described as follows:

Chapter 2: An overview of the geological development of the Cordillera and a geological description of the more local geology enclosing the Salta Basin, host to the Juramento mineralization; the chapter closes with a general introduction to the Juramento geology itself.

Chapter 3: A petrologic classification for the sediments of the Salta Group that form the stratigraphic sequence at Juramento; particular attention is given to the Yacoraite Formation which hosts the Juramento mineralization.

Chapter 4: Petrographic descriptions of the Yacoraite Formation, with details on paragenetic relationships to constrain the timing of mineralization.

Chapter 5: Descriptions of the sulphide mineralogy, including its characteristics and zoning, and the results from sulphur isotope analyses.

Chapter 6: A discussion of results given in previous chapters, with a focus on the interpreted environments of host-rock deposition and diagenesis, and of sulphide deposition.

Chapter 7: Principal conclusions of this study.

## **CHAPTER 2**

### **GEOLOGICAL SETTING**

#### **2.1 Cordilleran Geology**

The northwestern part of Argentina, between latitudes 22 and 28°S, lies in the Central Andes segment of the Andes mountains. This part of Argentina has been divided into several subparallel, north/south-trending, physiographic domains or provinces based on the geologic evolution of the eastern slope of the Andes mountains (Mendez et al., 1979; Mon et al., 1990) (Fig. 2.1).

From west to east, the first domain, lying along the border between Argentina and Chile, is known as the Main Cordillera (or Western Cordillera) and marks the western limit of the Argentinian Altiplano. It consists primarily of an alignment of late Tertiary-Quaternary volcanoes and volcanic flows in a terrain reaching more than 6000 metres in height. The second domain is the Altiplano proper (or high plateau, more commonly called the Puna), attaining about 5000 metres in elevation. It consists mainly of thrust sheets of Precambrian and Paleozoic sediments overlying Tertiary continental rocks exposed toward the east. The third domain, known as the Eastern Cordillera, forms the eastern limit of the Altiplano, with altitudes commonly higher than 5000 metres. It consists of a tectonically stacked Precambrian basement and Paleozoic sedimentary sheets thrust eastward over younger sediments. The easternmost domain of the Andes, the Sub-Andean Range, is made up of faulted anticlines of mainly Mesozoic and Tertiary rocks, varying in altitude between 800 and 3000 metres. Finally, to the east of

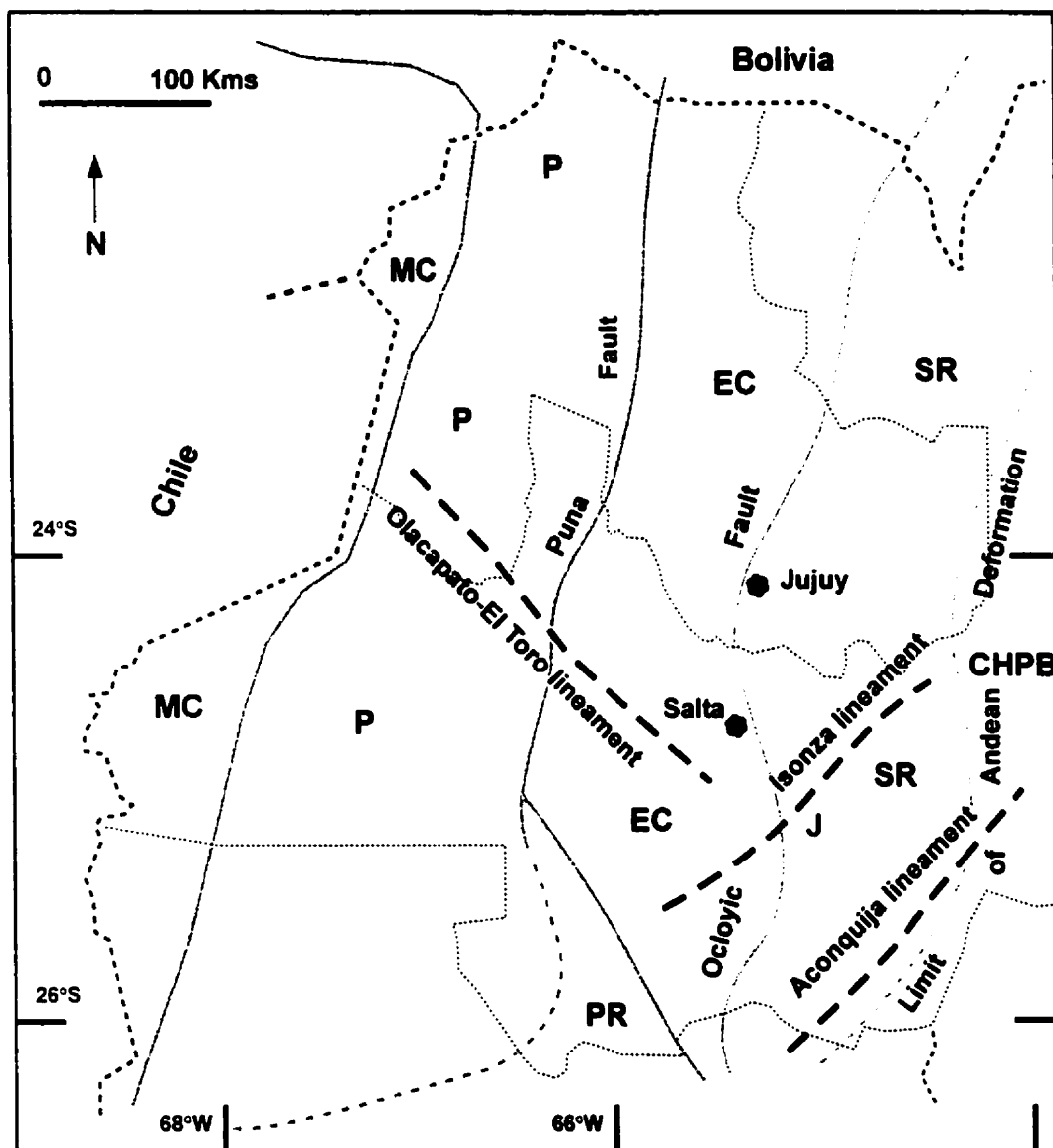


Figure 2.1: The physiographic domains of northwestern Argentina. CHPB = Chaco Parana Basin, EC = Eastern Cordillera, MC = Main Cordillera (or Western Cordillera), P = Puna, PR = Pampean Ranges, SR = Sub-Andean Ranges. Major N-S deep fractures that are marking domain limits are shown in wide grey lines. NE- and NW-trending lineaments are shown in dashed dark lines. J = Juramento deposit (approximate location).

the Andes lies a geologic province of subdued topography, the Chaco-Parana basin, consisting of Mesozoic, Tertiary and Quaternary sediments which overlie the South American craton. This basin extends well beyond the study area, into Uruguay to the east, into eastern Bolivia to the north, and into Brazil and Paraguay to the northeast.

South of 22°S, the Andean foreland, forming the Eastern Cordillera and the Sub-Andean Range, is replaced by the Pampean Range, which is composed of faulted blocks of Precambrian crystalline basement and Paleozoic granite.

#### 2.1.1 Geologic Evolution

The arrangement of the physiographic domains and the geologic characteristics of the Argentinian Central Andes resulted from successive diastrophic events which occurred at various crustal levels in a highly complex basement forming the root of the Andes (Mon et al., 1995; Tankard et al., 1995). The core, built during the 700-600 Ma Pan-American Orogeny, corresponds to the Brasiliano tectonic cycle. Structures related to this orogeny influenced the tectonics and the development of the later sedimentary basins, as described below.

The post-Precambrian tectonic evolution of the Central Andes can be divided into two principal orogenic cycles, the Hercynian cycle and the Andean cycle (Coira et al., 1982; Frutos, 1990; Mon et al., 1995). The deposition of Cambro-Ordovician sediments marks the beginning of the Hercynian cycle. These strata are open-marine sediments (mostly shales and phyllites) and pillow lavas which were deposited in a rapidly subsiding northwest-trending basin located between the present Sub-Andean Range and the Main Cordillera. The extension of the sediments to the west is dubious in this sector of the Central Andes (Ramos, 1988). Sedimentation and volcanism ended by the Late

Ordovician, in which period the rocks were folded during the Ocloyic (Taconic) Orogeny to form the Puna Arch. In the northern part of the Central Andes, this event corresponds to the accretion of the Arequipa microplate.

During the Silurian and Devonian periods, sediment accumulation occurred in two basins located on either side of the Puna arch. These basins had (and still have) north-northeast trends and occupy the present location of the Puna, the Eastern Cordillera and the western portions of the Sub-Andean Range. They are shallow-water, clastic sediments which were folded in the Late Devonian-Early Carboniferous during the Chañic (Acadian) Orogeny.

From Carboniferous to Lower Permian time, carbonates were deposited to the west of the Puna Arch and redbeds to the east. From Middle and Late Permian to Early Triassic time, these sediments were folded and exposed during the San Rafael (Appalachian) Orogeny and a magmatic arch formed at the location of the Main Cordillera. Peneplanization followed and marked the end of the Hercynian cycle.

The Andean cycle, Mesozoic and Cenozoic in age, is related mainly to the currently ongoing subduction of the Pacific Ocean lithosphere beneath the South American plate. It is characterized by an eastward migration of magmatic activity. Mountain-building resulted from compression due to rapid subduction and increased magmatic activity (Mon et al., 1995). This cycle started in mid-Triassic time with a strong marine transgression from west to east, reaching the present location of the Main Cordillera in Peru and Chile. Since the Lower Jurassic, a volcanic arch formed to the west of this basin.

In the Upper Jurassic-Cretaceous, the Araucanian (Nevadian) Orogeny affected all previous sediments in Chile. A new marine transgression followed in Early Cretaceous

time in a narrow back-arc basin occupying the area of the previous Jurassic basin. In this period, the magmatic arc started to migrate to the east and to affect the marine basin, such that the marine environment retreated eastward and the back-arc basin evolved toward continental conditions. This eastward migration was restricted to the western slopes of the Andes such that magmatism did not reach the eastern side of the Andes during the Mesozoic.

A different series of events occurred further inland. A rift with a northwest-southeast trend developed in the Late Jurassic-Early Cretaceous (Araucan Orogeny), extending from Peru and Bolivia southward to northwestern Argentina. This event marks the beginning of the Andean cycle in northwestern Argentina and coincides with the extensional tectonics of the Gondwana breakup and with the opening of the protoAtlantic Ocean. The rift was filled largely by syn-rift red-beds interlayered with coeval mafic volcanics and by post-rift sandstones and marine-lacustrine limestones (Campanian-Maastrichtian); the rift was finally filled by Eocene lacustrine and fluvial sediments. These sediments occupy the current domains of the Sub-Andean Range, the Eastern Cordillera and the Puna.

Inversion of the rift basin started during the Late Eocene-Early Oligocene Inca compressional event which interrupted sedimentation. Renewed sedimentation began in Oligocene-Miocene time, with continental sediments deposited in the Sub-Andean foreland basin and in the extensional intermontane basins of the Puna. During the Early-Late Miocene, Quechua deformation affected the Puna and the Eastern Cordillera, deforming the western flank of the rift sediments. In the Late Miocene-Pliocene, an ensialic magmatic arc developed in the Main Cordillera, representing the eastward migration of magmatism.

The latest orogeny, the Diaguita event, took place during Pliocene-Pleistocene time.

This orogeny deeply affected all previous sediments: it folded the Cretaceous and Tertiary sediments and reactivated the pre-Cretaceous basement structures. The Diaguita Orogeny extended further east than the Quechua Orogeny, and affected the Sub-Andean and Pampean ranges.

### 2.1.2 Structure

During the tectonic evolution of the Andes, several major faults developed. They influenced the emplacement of most Phanerozoic basins and, acting as thrusts and strike and slip faults, served as sites of stress relief during compressional periods (Baldi et al., 1980, 1984; Salfity, 1995; Tankard et al., 1995). They are the conjugate set of NE/SW-striking Aconquija lineaments, and NW/SE-striking Olacapato-El Toro lineaments that were formed in Neoproterozoic-Cambrian time. Also, the N/S-striking Puna and Ocloyic faults (Fig. 2.1) formed in Early Paleozoic time.

The Olacapato-El Toro and the Aconquija lineaments are megafaults which first developed during the evolution of the Precambrian core of the Andes, i.e., before the Hercynian cycle. To the south of the Aconquija lineament, the Eastern Cordillera and the Sub-Andean Range are replaced by the Pampean Range, delineating the southern limit of the future Puna in the Catamarca Province.

The Puna and Ocloyic regional faults, initially formed during the Hercynian cycle, now defined the margins of the Neoproterozoic-Cambrian basin which formed along the passive margin of Gondwana. They are believed to have acted as normal faults which were reactivated during the Ocloyic Orogeny. The basin was also inverted along this fault system to form the Puna Arch. This arch influenced the development of most Siluro-Devonian and Carboniferous-Permian basins.

The tectonic style changed during Mesozoic time (Andean cycle) when extension and rift formation generally prevailed. At first, during Triassic-Jurassic time, tectonic extension was related to a transtensional mode and later, during Jurassic-Cretaceous time, it was related to the opening of the Atlantic Ocean, assisted by the roll-back effect of subduction of the Pacific lithosphere to the west. During this period, movements on the northwest-trending and northeast-trending structures delineated the Andean rift basins which were the sites of most syn-rift sedimentation and volcanism.

During the Cenozoic, the tectonic style changed to compression and led to reversals on rift-basin faults. The strongest events occurred during the Quechua Orogeny, during which basin faults acted as thrust and strike-slip faults and resulted also in reactivation of older fault systems. In this phase, there was also overprinting of new faults and folds, most occurring subparallel to the line of subduction west of the Andes mountains.

## **2.2 Geology of the Salta Basin**

### **2.2.1 Developments in Late Mesozoic-Early Tertiary time**

As stated above, in Late Jurassic-Early Cretaceous time (including the Araucan orogenic phase), a rift developed in the Andes foreland along the Central Andes segment (Figs. 2.1 and 2.2). The north branch of the rift extended from northwestern Argentina to the north, through Bolivia, and into southern Peru. Other branches extended to the northeast into Paraguay (the northeast branch) and to the west into Chile (the western branch), transecting the Puna, the Eastern Cordillera and the Sub-Andean ranges (Salfity, 1988; Camoin et al., 1994). A number of local basins developed within the rifts: the Central Andean Basin in the north branch, the Purilactis Basin in the western

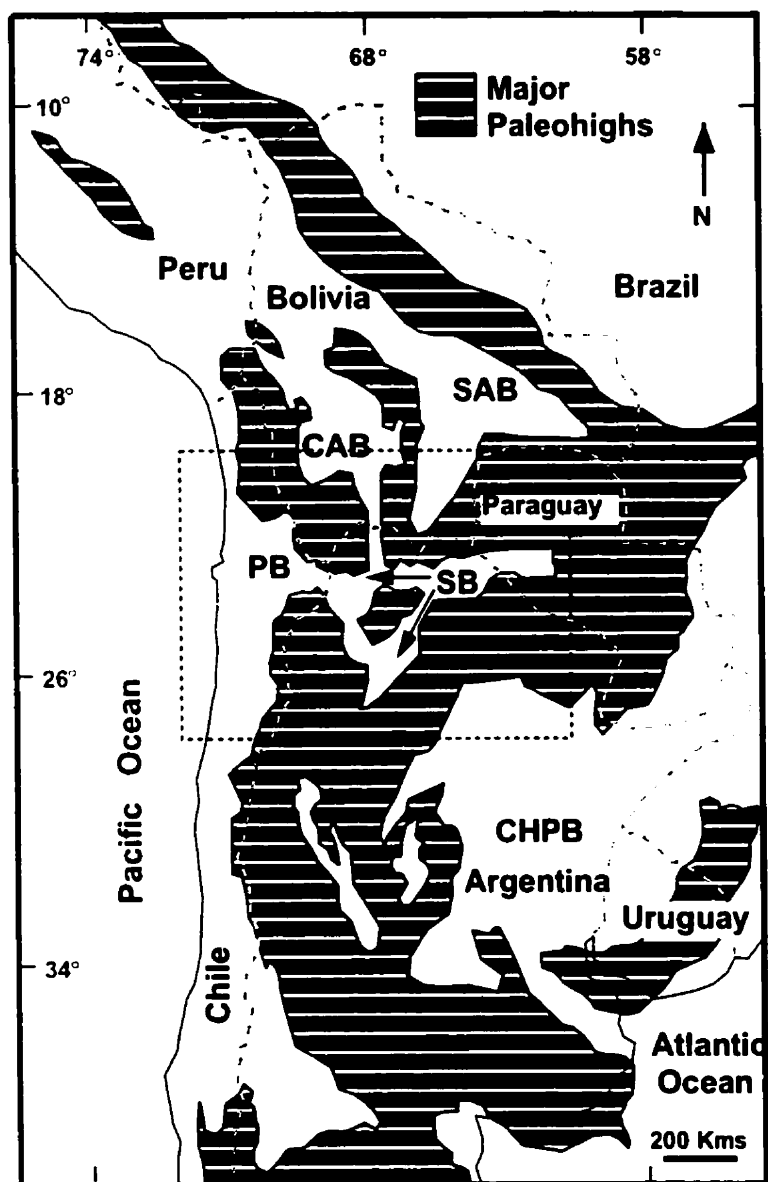


Figure 2.2: The extent of Late Mesozoic-Early Tertiary rifting, modified after Mon and Salfity, (1995). CAB = Central Andean Basin, CHPB = Chaco Parana Basin, PB = Purilactis Basin, SB = Salta Basin (arrows show sub-basins). Square outlined in dashed lines shows the area of Figure 2.3.

branch, and the Salta Basin of northwestern Argentina at the triple junction of all branches.

The Salta Basin developed around the so-called Salta-Jujuy high (Fig. 2.3), using previously-formed normal faults having northeast and southwest trends (Salfity, 1979; Tankard et al., 1995). The most relevant features of the Salta Basin are the Izonza lineament, the Olacapato-El Toro fault, the Aconquija lineament, the Cobres lineament, the Tomasito lineament and the Los Blanquitos lineament. These structures determined the areas of sedimentation (i.e., basins), as well as the formation of adjacent arches. To the southwest, the Salta Basin is limited by the Transpampean Arch and to the southeast by the Pampean Arch. The northeastern branch of the rift in the Salta Basin had two margins: the Michicola Arch to the north and the Quirquincho Arch to the south. The north branch also had two margins: the San Pablo High to the west, and the Condor Arch to the east.

The Salta Basin is divided into sub-basins formed along each of the rift branches. The sub-basins started as isolated rift branches that later became interconnected, forming depressions and basin highs (Salfity, 1995). The depressions became centres of sediment accumulation (depocentres) known as the Alemania, Metan and El Rey sub-basins to the south of the Salta-Jujuy high, the Sey depocentre to the west, the Tres Cruces to the north, and the Lomas de Olmedo to the northeast. These depocentres were connected through basin highs or swells. The Alemania and Metan depocentres were interconnected by the Canuto swell, a positive element immediately to the west of the Oclayic fracturation front; the Metan and El Rey were connected by the Las Viboras swell; and the El Rey depocentre was united with the Lomas de Olmedo depocentre by the Los Gallos and Cachipunco swells. The Tres Cruces depocentre was connected to the north to the Central Andean basin by The Tres Cruces swell, and the Sey depocentres was united with the Purilactis basin to the west through the Huaytiquina swell (Marquillas, 1984; Salfity, 1994).

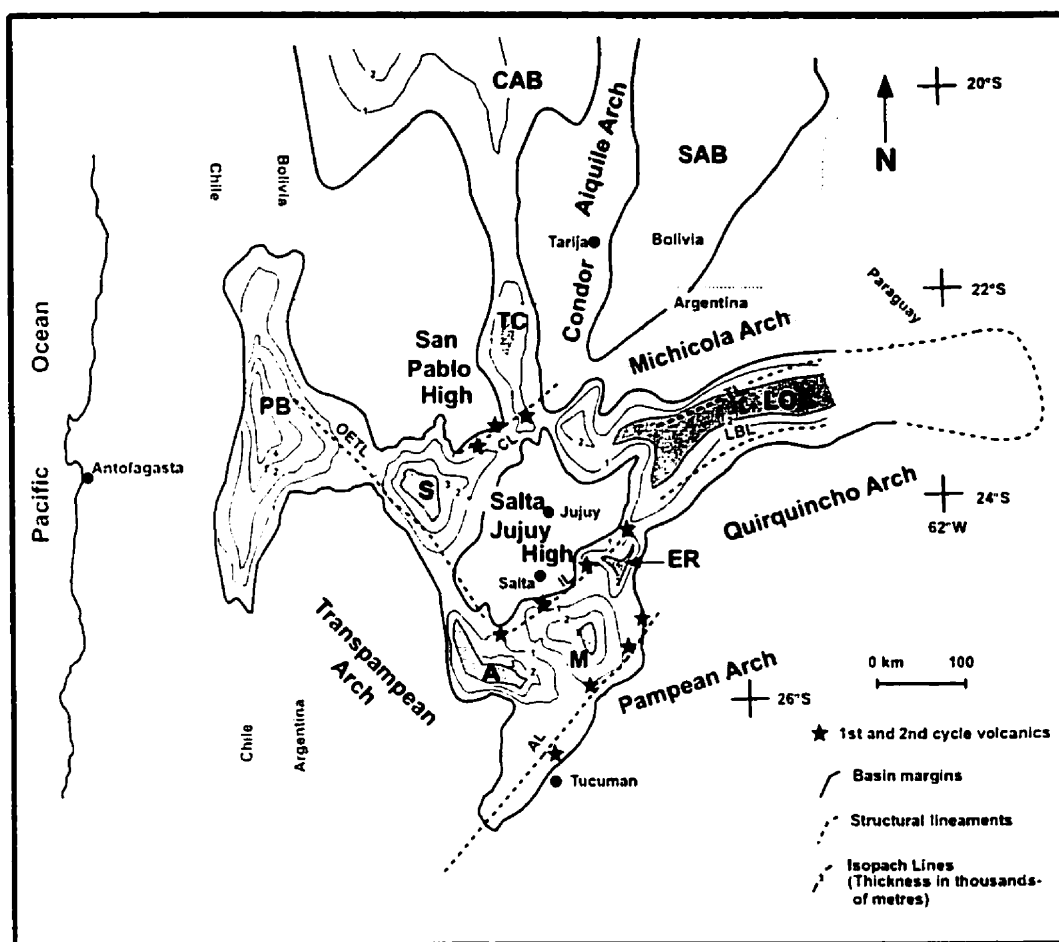


Figure 2.3: Isopach map of the Salta Basin during the synrift period (Pirgua Sub-Group), showing the major sub-basins (shaded), emerged areas and deep-seated NW- and NE-lineaments. Note the location of volcanism along these lineaments, and how the basin emplacement is influenced by them. Sub-basins: **LO** = Lomas de Olmedo, **ER** = El Rey, **M** = Metan, **A** = Alemania, **S** = Sey, **TC** = Tres Cruces. Lineaments: **AL** = Aconquija lineament, **IL** = Isonza lineament, **OETL** = Olacapato-El Toro lineament, **CL** = Cobres lineament, **TL** = Tomasito lineament and **LBL** = Los Blancitos lineaments. Neighbouring basins: **PB** = Purilactis Basin (in Chile), **CAB** = Central Andean Basin and **SAB** = Sub Andean Basin (in Bolivia). Adapted from Marquillas et al. (1994).

The Salta Group of sediments filled the Salta basin. Two periods of sediment deposition are recognized: syn-rift sedimentation and post-rift sedimentation (Marquillas and Salfity, 1988) (Fig. 2.4). During syn-rift sedimentation, the pre-rift basement rocks of various ages were unconformably covered by the Pirgua Subgroup (Fig. 2.3). These continental redbeds are divided in two tectonosedimentary units (Bosso et al., 1984): the lower unit, the La Yesera Formation, represents sedimentation during active faulting, with maximum accumulation of a high-energy alluvial facies along the basin borders and a passage to fluvial, eolian and distal playa facies towards the interior; the upper tectonosedimentary unit, represented by the Las Curtiembres and Los Blanquitos formations, fills minor sub-basins. In the case of the Las Curtiembres Formation, a meandering-stream facies indicates that sedimentation occurred during minor normal faulting. In the case of the Los Blanquitos Formation, stream-flood and sheet-flood sediments indicate slight reactivation of faulting during late syn-rift sedimentation in the Salta Basin (Bosso et al., 1984).

During the post-rift phase, the basin continued to subside and sedimentation continued to take place, characterized by an apparent marine transgression and shallow-marine sedimentation represented by the Balbuena Subgroup and the Santa Barbara Group which overlap the continental Pirgua Subgroup. The Balbuena Subgroup consists of shallow-water shore-clastic sediments and carbonates. The base of the subgroup is represented by the shore sandstones of the Lecho Formation (Marquillas et al., 1988). The overlying Yacoraite Formation (Fig. 2.5) consists of limestones and calcareous-dolomitic siltstones deposited in a shallow marine or lacustrine environment, with a gradational contact downward into the underlying Lecho Formation (Marquillas 1984, 1985; Palma, 1984). The Yacoraite Formation, the principal host of stratiform copper-silver mineralization in the Salta area, is described in more detail below (see section 2.2.2).

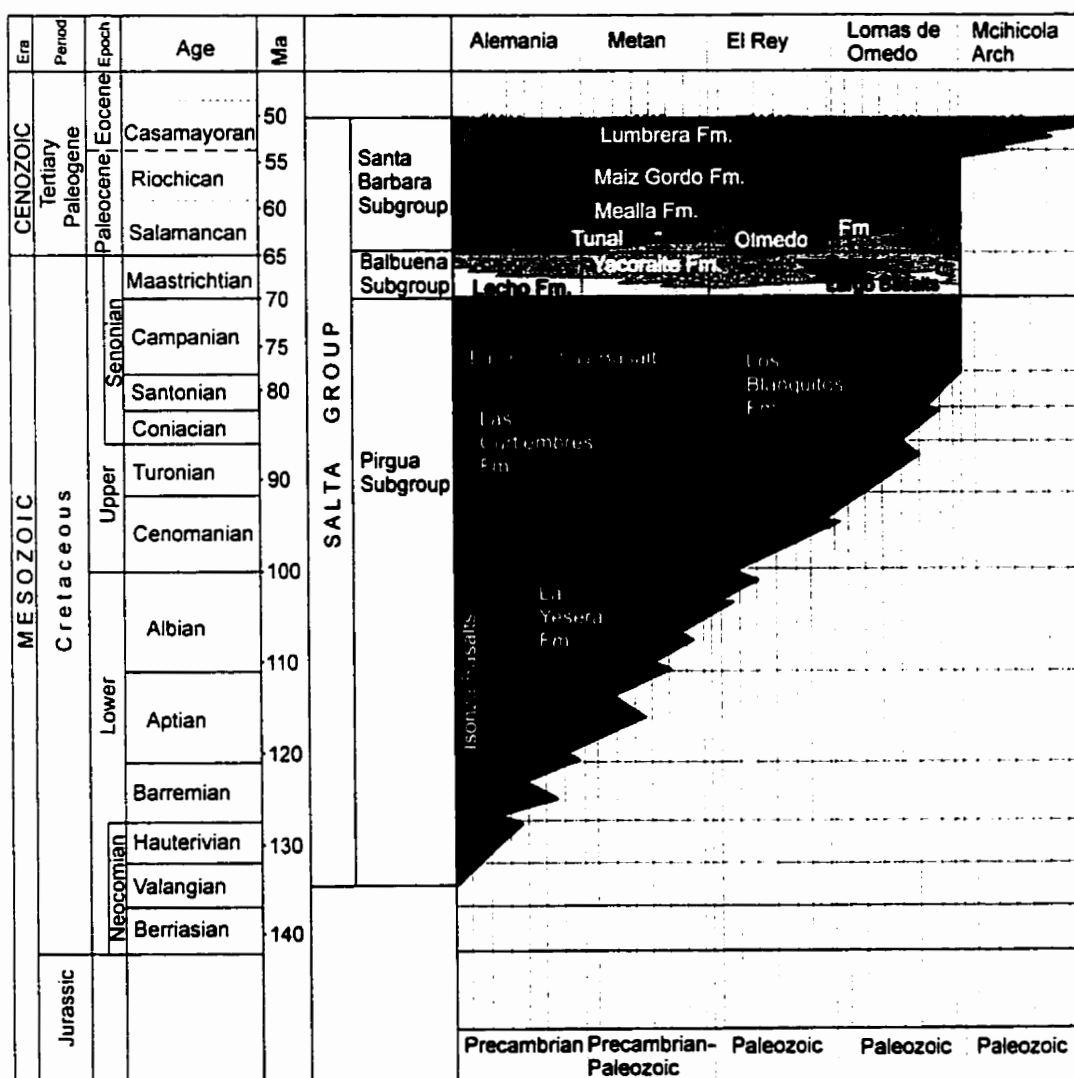


Figure 2.4: The stratigraphy and inter-basin correlation of the Salta Group sediments among the principal depocenters of the Salta Basin. Modified after Marquillas and Salfity (1988).

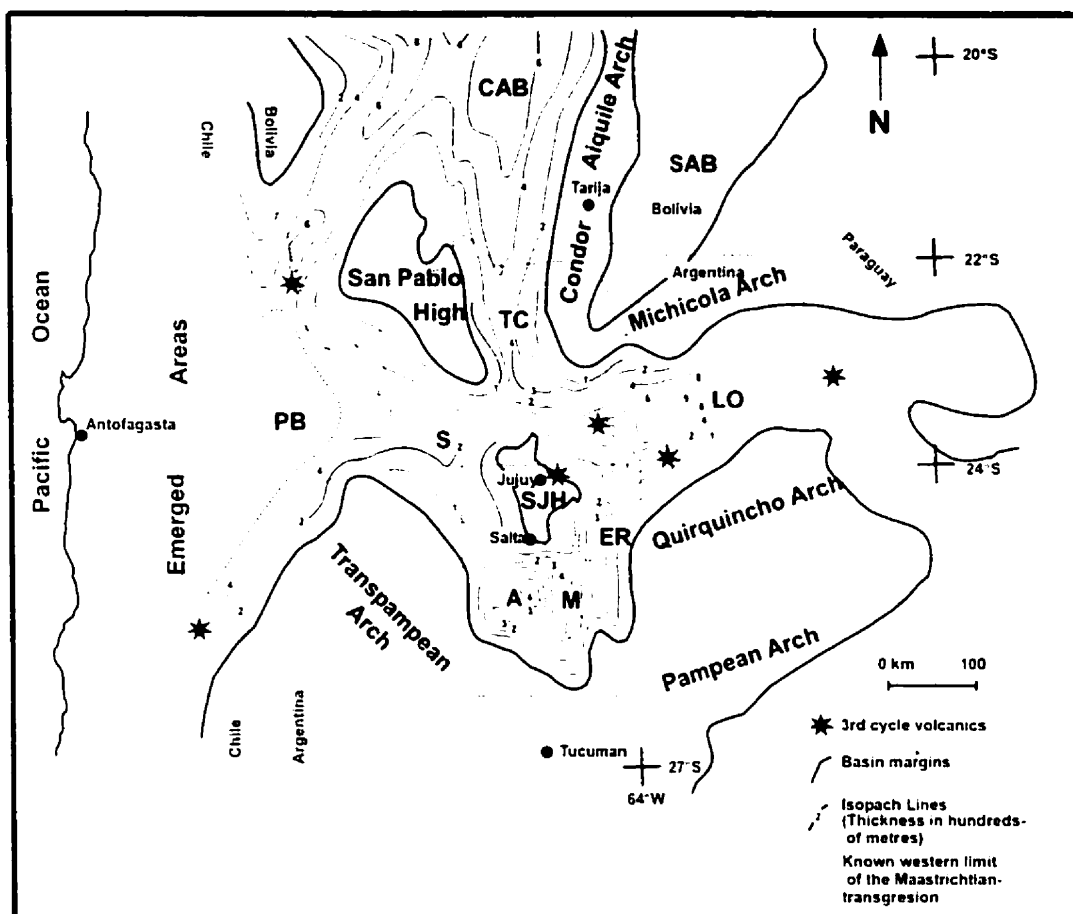


Figure 2.5: Isopach map of the Yacoraite Formation during post-rift period, showing the major depocenters (same as Figure 2.3) and volcanic episodes. Note the encroachment of the Salta-Jujuy high (SJH). Square shows the area of Figure 2.5. Same abbreviations as in previous figure. Adapted from Marquillas et al. (1994).

The overlying Tunal and Olmedo formations, marking the transition to the Santa Barbara Subgroup, are interpreted as fluvial-lacustrine green siltstones (Espisúa et al., 1983, Palma, 1984). The stratigraphically higher Santa Barbara sediments, the Mealla, Maiz Gordo and Lumbrera formations, are composed of continental clays and siltstones covering part of the Quirquincho Arch to the east. These continental units are the youngest sediments before the beginning of the structural inversion of the rift basin and development of a local foreland basin during the Late Eocene Inca tectonic phase. That basin hosted the synorogenic sediments of the Oran Group, that cover the Salta Group of sediments (Marquillas et al., 1988; Mon et al., 1995; Cristallini et al., 1997).

Floods basalt are intercalated with various formations of the Salta Group in the Salta Basin. The regional structural lineaments apparently served as conduits for the upward flow of mafic magma along the basin borders. The first two syn-rift volcanic units are hosted by the Pirgua Subgroup. Of these, the stratigraphically lower flows are intercalated with the La Yesera Formation along the Cobres, Isonza and Aconquija lineaments, whereas the second, the Las Conchas basalts, are interfingered with the upper parts of the Las Curtiembres Formation in the Tres Cruces sub-basin. A third volcanic unit, which formed during the post-rift event, is hosted by the Yacoraite Formation and took place along the Los Blanquitos and Tomasito lineaments in the Lomas de Olmedo sub-basin. Several intrusive bodies also occur along the Cobres lineament and to the south of the Alemania sub-basin. These intrusions are of the same age as the first and second basalts units (Marquillas and Salfity, 1988). Tuff beds also are present within the Yacoraite Formation; up to three tuff units have been identified in the Metan sub-basin (Marquillas et al., 1984).

### 2.2.2 The Yacoraite Formation

Much of our interpretation of the emplacement of the Juramento mineralization depends upon the interpreted environments of sedimentation and diagenesis of the host Yacoraite Formation. The following general descriptions of this formation are taken mainly from Marquillas (1984), Marquillas et al. (1984) and Palma (1984). A more detailed description of the various sedimentary facies is given in our petrographic report (see Chapter 3).

The Yacoraite Formation of Campanian-Maastrichtian age is a calcareous unit belonging to the Balbuena Subgroup, this Subgroup of Senonian Superior-Paleocene age (see Fig. 2.4). The Balbuena Subgroup is part of the Salta Group of Lower Cretaceous-Eocene age (Marquillas, 1984, 1986).

The Yacoraite Formation represents a major change in the style of sedimentation between the continental redbeds of the underlying Pirgua Subgroup and the continental clays and siltstones of the overlying Santa Barbara Subgroup. The formation is widely distributed across northwestern Argentina and neighbouring countries where the equivalent strata are known as the Vilquechico Formation in southern Peru, the El Molino Formation in Bolivia, the Quebrada Blanca Formation in northern Chile and other equivalents in the subsurface of Paraguay (Marquillas et al., 1988).

Figures 2.5 and 2.6 show various structural elements in the Yacoraite Formation: positive areas (arches and highs), sub-positive areas (swells) and negative areas (sub-basins or depocentres). These structural elements controlled the type and thickness of sedimentation, resulting in up to 300 metres of sediments in the center of the Salta Basin. They also influenced the distributions of the sandy and carbonate facies crucial to our interpretations of sedimentary environments. Sandy facies are most abundant in

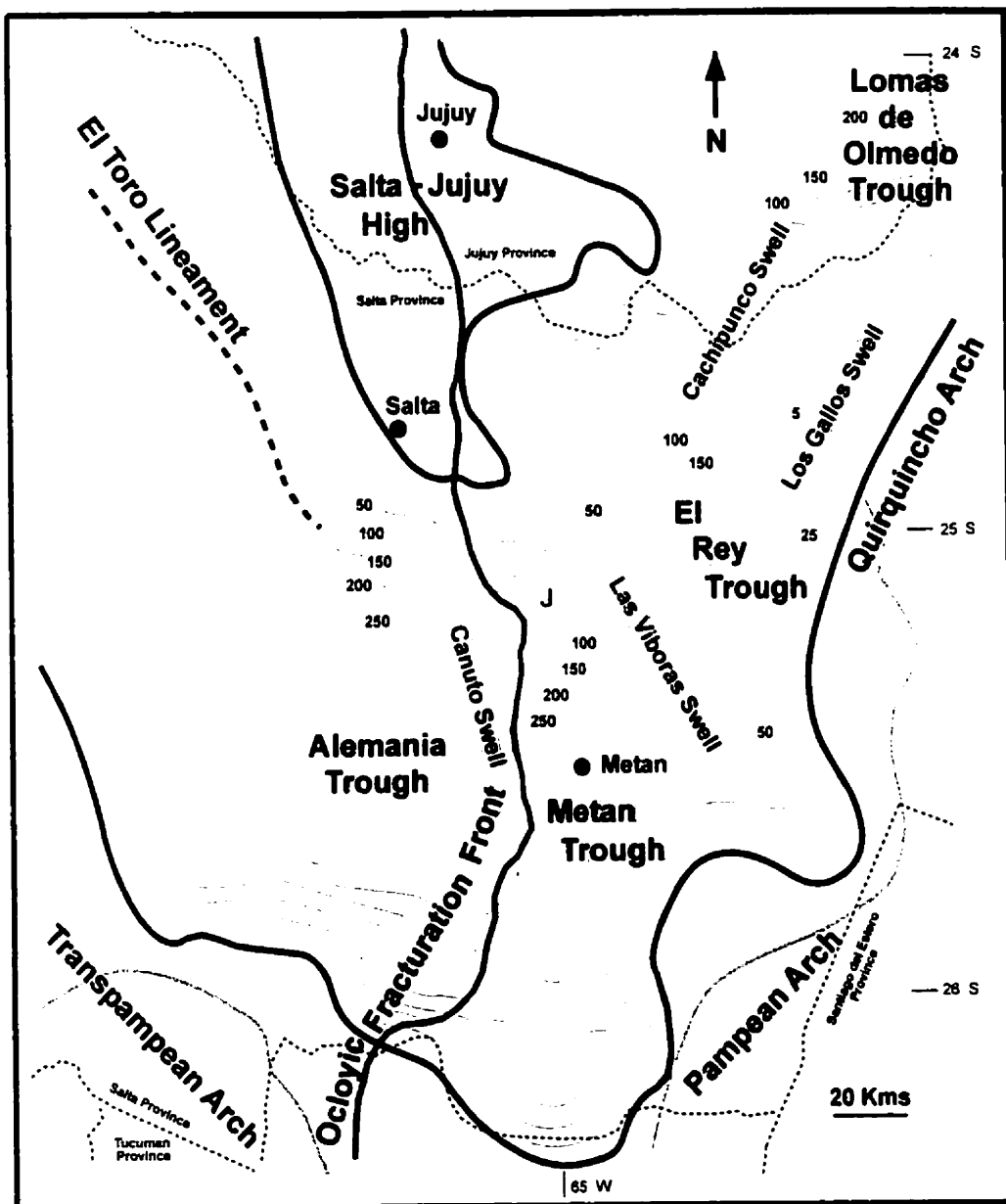


Figure 2.6: Isopach map of the Yacoraite Formation (solid line) in the southern portion of the Salta basin, showing basin highs (swells) and depressions (throughs as shaded areas). Greyish lines are the limits of the Pirgua Sub-Group. See location of Jaramento (J) with respect to the Metan through. Adapted from Marquillas (1984).

the southern portion of the Salta Basin (Marquillas et al., 1984), probably because of the proximity to a river draining the area to the south of the basin (Gayet, 1993).

Calcareous facies are dominant to the north, especially in the Lomas de Olmedo Basin and around the Salta-Jujuy high. The latter subsided slowly and acted as a stable carbonate platform (Marquillas et al., 1984; Mon and Salfity, 1995).

A variety of sedimentary facies are present in the Yacoraite Formation: oolitic grainstones, packstones, mudstones, wackestones, siltstones, stromatolitic boundstones and tuffs. These sediments were deposited mainly under hot, arid conditions (forming gypsum and salt and moulds of their crystals) where the depth of water was highly variable and resulted in frequent subaerial exposures (and consequently in the formation of mudcracks) with fauna of a mixed, marine-lacustrine environment (charophyta, ostracoda and marine fishes).

The study of relationships between these facies has resulted in the recognition of a general, repeated sedimentary cycle in the Yacoraite Formation. It consists of passages from low-energy calcareous sediments, to higher energy calcareous sediments, and finally to low-energy fine siliciclastics (Marquillas, 1984, 1986; Palma, 1984). The precise environment of deposition remains partially ambiguous because the Yacoraite Formation presents evidences of both marine and lacustrine environments. Marquillas (1984, 1986) interpreted the environment as a restricted carbonaceous basin developed in an epeiric shallow-water basin of marine or lacustrine character (also proposed by Sempere, 1995). Palma (1984) concluded that the Yacoraite Formation is a well-developed lacustrine deposit because the El Molino Formation, correlated with the Yacoraite Formation in the Central Andean Basin (Bolivia), is interpreted as having been deposited in a saline lacustrine environment (Rouchy et al., 1993; Camoin et al., 1997).

The Yacoraite Formation is important for its stratigraphically extensive rift-related copper-silver mineralization from Bolivia (Rouchy et al., 1993; Blanc-Valeron et al., 1994; Camoin et al., 1997) to the southern end of the Metan sub-basin. Some thirty mines, adits and old workings are recorded throughout the Salta Basin (Mason, 1996). In the Metan sub-basin, manganese oxides, copper, silver, lead and zinc sulfides are described in certain stratigraphic profiles including that of the Juramento property (Angelelli, 1950; Espisúa et al., 1983; Marquillas, 1984, 1986; Marquillas et al., 1984).

The Yacoraite is also considered a source-rock, trap and seal for hydrocarbons (Mon et al., 1995). In the Salta Basin, oil and gas are exploited in the Lomas de Olmedo and Metan sub-basins. Hydrocarbon generation and migration are interpreted to have been driven by Tertiary deformation, probably at the end of the deposition of the Oran Group sediments (Late Oligocene to Late Pliocene-Early Pleistocene). Hydrocarbons fill the primary porosity of sandstones in the Lomas de Olmedo sub-basin and fill the secondary fracture porosity created by fracturing of Tertiary age throughout the Sub-Andean Range.

### **2.3 Property-Scale (Juramento) Geology**

The Juramento prospect (Fig. 2.6) is located in the northwestern margin of the rift-related Metan sub-basin, along the south margin of the Salta-Jujuy high immediately to the east of the Canuto swell and the Oclayic fracturation front. Many property-scale features were little known prior to this evaluation by Paramount.

#### **2.3.1 Structures**

The Juramento area includes two prominent ridges with generally north-south strikes (the Cerro del Plomo and the Cerro del Cobre), separated by a small valley followed by

an affluent of the Jabali Creek (Fig. 2.7). Both ridges converge at the south end of the prospect to form the El Condor ridge. At the north end, the Cerro del Plomo ridge turns towards the northwest and gradually decreases in altitude. The ridges are bordered by two reverse faults of north-south strike, with several transverse faults of ENE-ESE trend (Rotzien et al., 1998). Another ridge of north-south strike, the Cerro Oeste, is located to the west of the Jabali Creek.

The Cerro del Cobre is a highly-deformed area. With repeated fracturing and brecciation, the zone is believed to be a tectonic stack of imbricated slabs of west-dipping sediments. Towards the southern areas of the property, near the Elba adit, a fracture of ENE-trend is believed to indicate a change in the structural domain; south of the fault, the bedding dips east. At the north end of Cerro del Plomo, the dips of bedding suggest the closure of a north-plunging fold; however, this interpretation is not confirmed in drill sections. In the central section of Cerro del Plomo, the interpreted prolongation of the ENE- and ESE-trending structures is believed to have been responsible for important variations in bedding attitudes and for an overturned stratigraphy. Based on the stratigraphic attitudes and the general disposition of the sedimentary units, the overall Juramento prospect is interpreted to be a hinge-fold anticline plunging north, dissected by later ENE- ESE-trending transcurrent faults.

### 2.3.2 Stratigraphy

Several stratigraphic sections of the Salta Group are present on the property (Fig. 2.8). The oldest rocks are Devonian metasediments composed of well-lithified pinkish sandstones cropping out to the south of Juramento and along the ridge named Cerro Oeste, immediately to the west of the Jabali Creek. These rocks are considered to be the basement of the Mesozoic sedimentary section in the area (Marquillas, 1986).

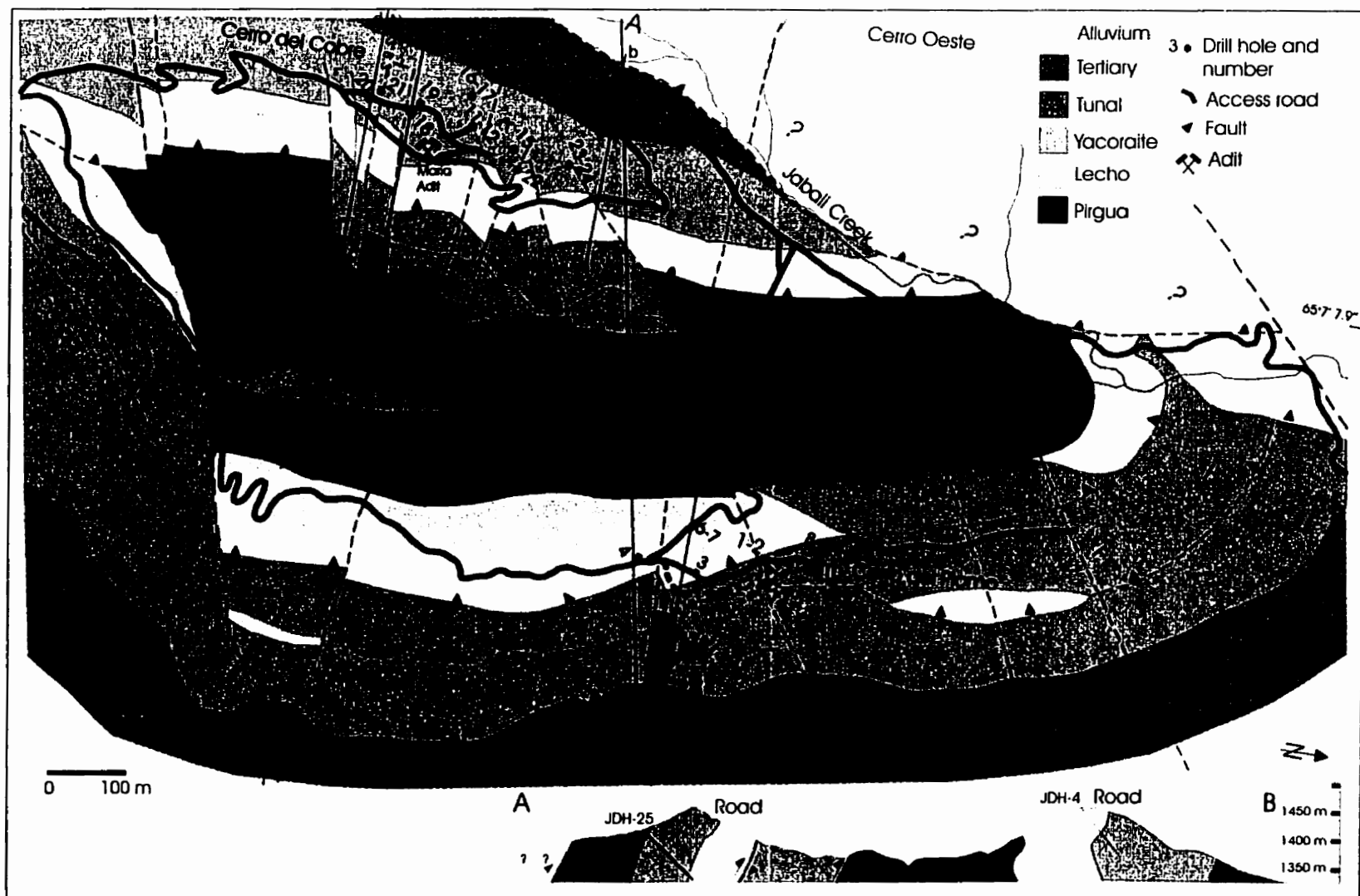


Figure 2.7: Geological map and cross-section of the Juramento property. Modified after Rotzien and Wormald (1998).

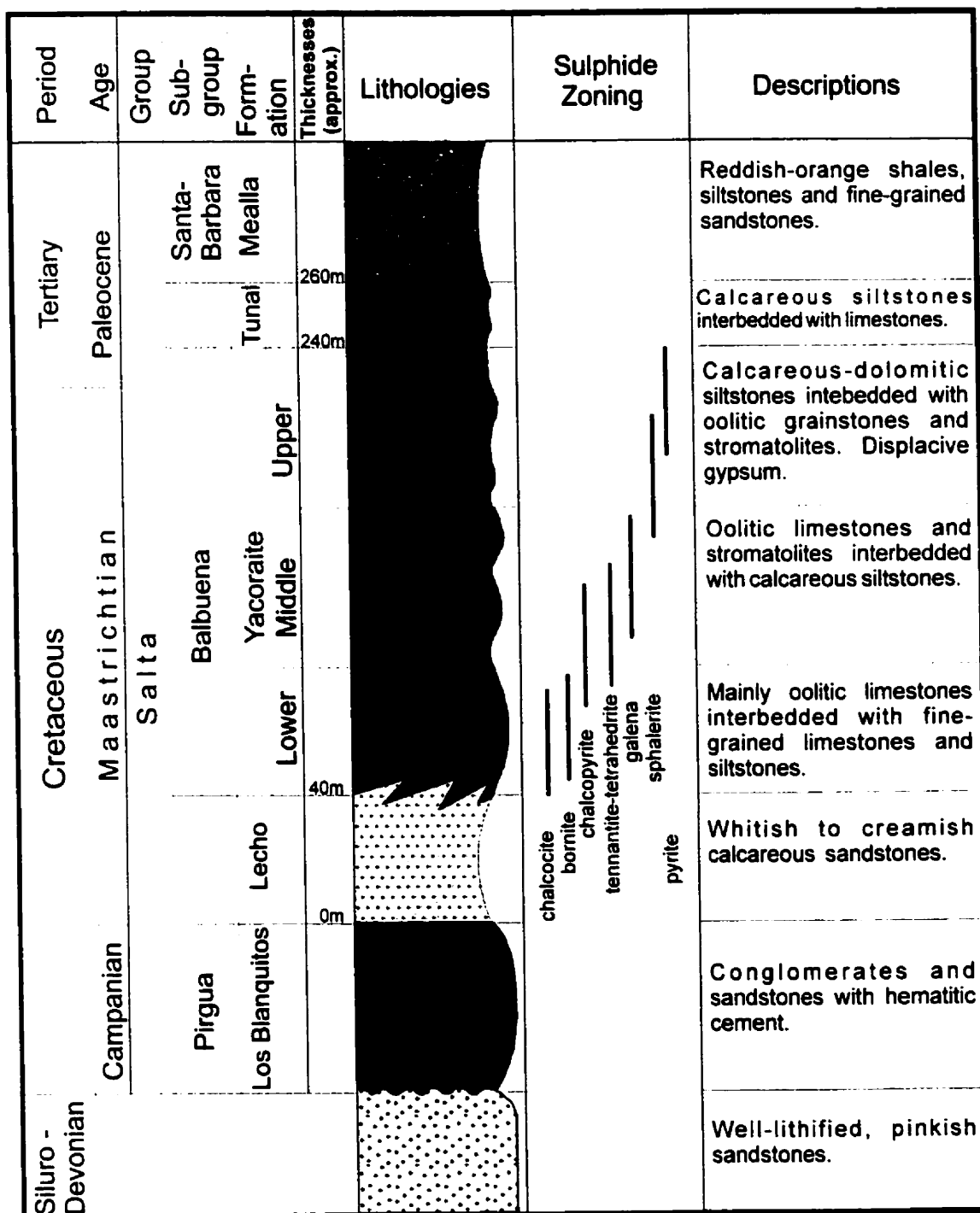


Figure 2.8: Schematic stratigraphic column for the Juramento property. Shows the major stratigraphic units of the Salta Group and general primary sulphide zoning.

The Devonian rocks are unconformably covered (the stratigraphic contact is seen only at Cerro Oeste) by the Pirgua Subgroup (a fault contact in the south is mentioned by Rotzien, 1998). These sediments are believed to belong to the Los Blanquitos Formation (Espisúa et al., 1983). The Los Blanquitos sediments consist of redbed conglomerates and sandstones, commonly including gypsum, basalt clasts and veins of specular hematite. The thickness of the Pirgua along the ridge immediately to the west of the Jabali Creek is estimated to be 200 to 300 metres, but the full thickness of the redbeds cannot be determined on the Juramento property itself. However, on Cerro Oeste, the thickness is less than the 800 to 3000 metres measured in depocentres elsewhere in the Salta basin, suggesting that our field area lies close to a basin margin.

The overlying Balbuena Subgroup consists of three formations lying with normal conformable contacts on the Pirgua Subgroup. The Lecho Formation has thicknesses of up to 170 metres, contrasting significantly with the 30 to 40 metres average thickness for this formation elsewhere in the basin; its true thickness is difficult to assess in the Juramento area due to fault repetition. The Yacoraite Formation lies with a conformable gradational contact above the Lecho Formation. The minimum thickness of the Yacoraite unit is 45.5 metres; due to fault repetitions, it exceeds 200 metres in thickness at Cerro del Plomo.

The Yacoraite Formation is divided into three units for correlation purposes (no sedimentological implications are intended because sufficiently detailed studies have not yet been done). The Lower Yacoraite is characterized by an abundance of oolitic grainstones interbedded with other fine-grained calcareous strata and siltstones. The Middle Yacoraite is characterized by a lower abundance of oolitic grainstones and an increase in the abundance of calcareous-dolomitic fine-grained clastic sediments; the base of this section is identified by the appearance of stromatolitic boundstone. The Upper Yacoraite is characterized by the predominance of marls and siltstones.

The uppermost unit of the Balbuena Subgroup, the Tunal Formation, is observed in some drill holes and at the eastern end of trench B on Cerro del Plomo (Fig. 2.6). The contact with the Yacoraite Formation is conformable. The sediments consists of green siltstones and marls with minor amounts of carbonate. The thickness of the Tunal Formation is approximately 15 metres in JDH-25.

Undifferentiated reddish Tertiary siltstones and claystones cover the Balbuena Subgroup. They are part of the Santa Barbara Subgroup and are visible on the eastern slope of the Cerro del Plomo ridge and on the western slope of the Cerro del Cobre ridge. Their thickness is not established in the Juramento area because only the basal section is seen: in trench B on Cerro del Plomo, the basal thickness is estimated to be some hundreds of metres.

The copper-silver mineralization of Juramento is hosted mainly in the Yacoraite Formation and is only locally and partially hosted by the Lecho Formation. As explained below, this distribution is related to special conditions of Lecho (e.g., the presence of pyrite) and to the weathering of the primary mineralization of the Yacoraite Formation (visible in the Maria adit; Fig. 2.6).

## **CHAPTER 3**

### **HOST-ROCK PETROLOGY**

The following petrological descriptions are given to provide fundamental information on the environments of sedimentation for the host strata of the Juramento area. In turn, this information allows us to interpret the context of copper-silver emplacement in these sediments.

#### **3.1 Pirgua Subgroup**

These sediments, interpreted to be equivalent to the Los Blanquitos Formation (Espisúa and Amengual, 1983), are the oldest rocks from the Salta Group cropping out at Juramento (see Figs. 2.4, 2.7 and 2.8). They are dark-reddish strata with no clear stratification, comprising a clastic series of sandstones and conglomerates deposited in a continental environment. A pervasive hematitic cement confirms the continental affiliation of these sediments.

Sample 8 (DDH JDH-5, 39 m), a representative sample of the Pirgua redbeds (Figs. 3.1 and 3.2), is a sandstone (using the Udden-Wentworth scale; in Adams et al., 1984). The detrital clast size varies from fine- to coarse-grained sand, with a matrix of coarse-grained silt or finer grains, and a cement of hematite. Sand grains have low sphericities and subrounded to subangular shapes (using Pettijohn's classification; in Adams et al., 1984). The principal grain compositions are quartz (monocrystalline and polycrystalline), feldspar (orthoclase and perthite), plagioclase, microcline, white mica,

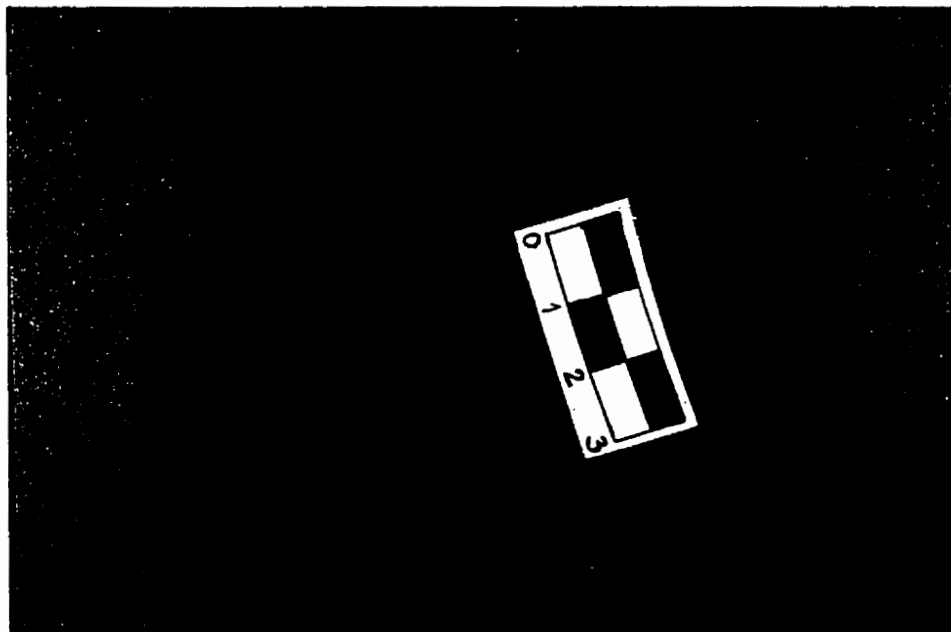


Figure 3.1: Drill core sample 8 from Pirgua sediments, JDH-5 m 39. The sediments correspond to sandstones with dark reddish color due to iron oxydes cements. CS. Scale is in centimetres.

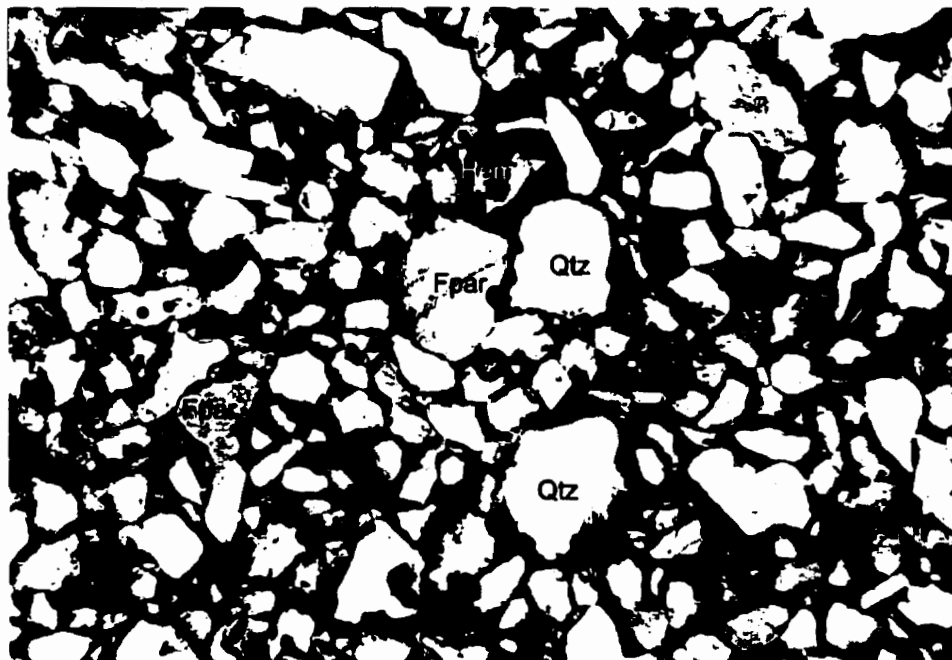


Figure 3.2: Sandstone from the redbeds. Note the angular nature of clasts and their varying size, showing immaturity of the sediment. Clasts are mainly: quartz (Qtz) and K-feldspar (Fpar). Cement consists of hematite (Hem). Sample 8 (same as above), PTS, PPL, FOV = 2.15 millimetres.

tourmaline and rock fragments. In some cases, the contacts between grains are concavoconvex due to compaction of the sediment. Some nodules of coarse-grained calcite cement fill voids. These nodules are interpreted to be pseudomorphs of gypsum or fillings of open spaces by late coarse-grained calcite during uplift and denudation. The sediment is considered an immature sandstone due to the size and shape of grains and the mineralogy of the clasts.

### **3.2 Lecho Formation (lower Balbuena Subgroup)**

This sediment represents the transition between the redbeds of the Los Blanquitos Formation and the carbonates of the Yacoraite Formation. The colour is light grey (essentially white) and in some areas the unit is highly friable (Maria adit, Cerro del Cobre). Within a single borehole, it is possible to detect wide variations in the proportions and size of the principal grain types and allochems of this sandstones (samples 1, 2 and 3; see below), indicating a proximity to the gradational contact with the Yacoraite Formation and/or to rapid facies changes. The following samples were taken from drill hole JDH 1 (see Fig. 2.7).

Sample 3 (DDH JDH 1, 104.3 m), stratigraphically lowest in the Lecho section, is a moderately well-sorted sandstone (Figs. 3.3 and 3.4). Grains are of medium to fine sand size and comprise up to 90% of the sediment; the remainder is a matrix of coarse-grained silt and carbonate cements (authigenic microcrystalline grains of a few tens of micrometres in size). The principal sand grains are quartz, feldspar, perthite, tourmaline and white mica. A few lumps or aggregates (less than 3% of the total sample volume) of micritic composition are observed. Very fine-grained framboidal pyrite is found in this micrite. The lumps are interpreted to be rolled micrite of algal origin; they could also be pellets. These terrigenous clasts are of low sphericity and are subrounded to subangular in shape.

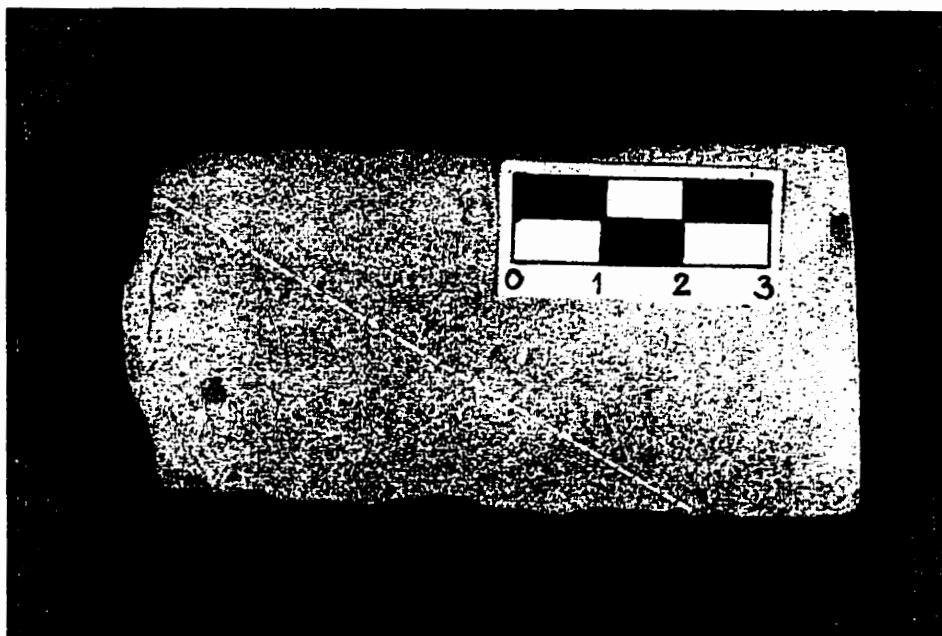


Figure 3.3: Drill core sample from Lecho Formation. This is a sandstone, note the whitish-yellowish colour. Note sulphides (white arrow) aligned in bedding planes (white dashed line). Sample 2, CS. Scale is in centimetres.

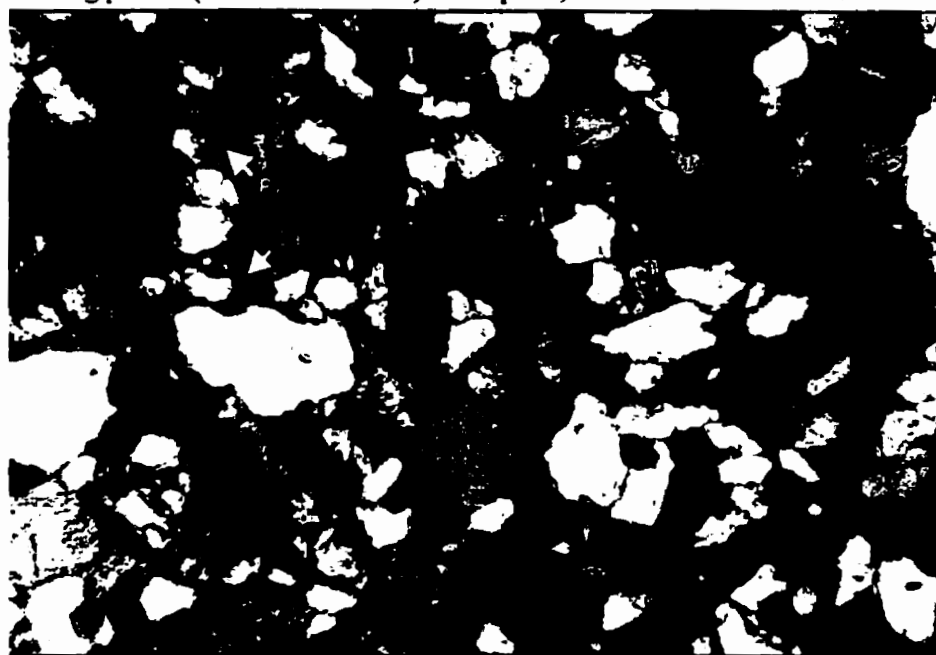


Figure 3.4: Calcareous sandstone from the Lecho Fm., composed mainly of quartz and feldspars grains. Note the calcite cement (Ca), consisting of small rhombohedrons (arrow) around grains, showing little cementation. Also, note pyrite (py), inside a micritic agglomeration interpreted as organic in origin. Sample 2 (same as above), PTS, PPL, FOV = 2.15 millimetres.

Samples 1 and 2 (DDH JDH 1, 74 m and 83 m, respectively) show (Fig. 3.5), relative to sample 3, a diminution in the proportion of terrigenous grains (30-40%) and an increase in allochems (ooids, oncoids and lumps: 40%) as well as in the amount of carbonate matrix and cement (microspar: 20-30%). The size of the principal grains increases to coarse sand. The ooids are of the same size as of the terrigenous clasts.

The clastic grains consist of quartz, feldspars, tourmaline, white mica and allochems. Terrigenous grains are rounded to subrounded and some are coated by a radial carbonate fringe. The matrix is composed of calcitic microspar, probably resulting from recrystallization of micrite during burial.

The environmental differences would appear to be minor, however between samples 1 and 2 and sample 3 are interpreted as resulting from different environments of deposition: sample 3 formed in an aerielly exposed or sporadically moistened sediment, whereas samples 1 and 2 were probably formed in shallow water at the same time as the coating of ooids by calcite and the deposition of clastic terrigenous grains and their matrix.

### **3.3 Yacoraite Formation (middle Balbuena Subgroup)**

The calcareous sediments of the Yacoraite Formation overlie the sandstones of the Lecho Formation. Freshly broken surfaces are dark grey, but they weather to a typical orange-yellow colour, probably due to the oxidation of pyrite. Consequently, the Yacoraite is easily recognized from a distance, facilitating regional prospection. The contacts are gradational at the base and conformable at the top of the formation. The most obvious megascopic characteristic is the presence of oolites, which diminish in abundance toward the Upper Yacoraite. Fractures containing hydrocarbons are also abundant.

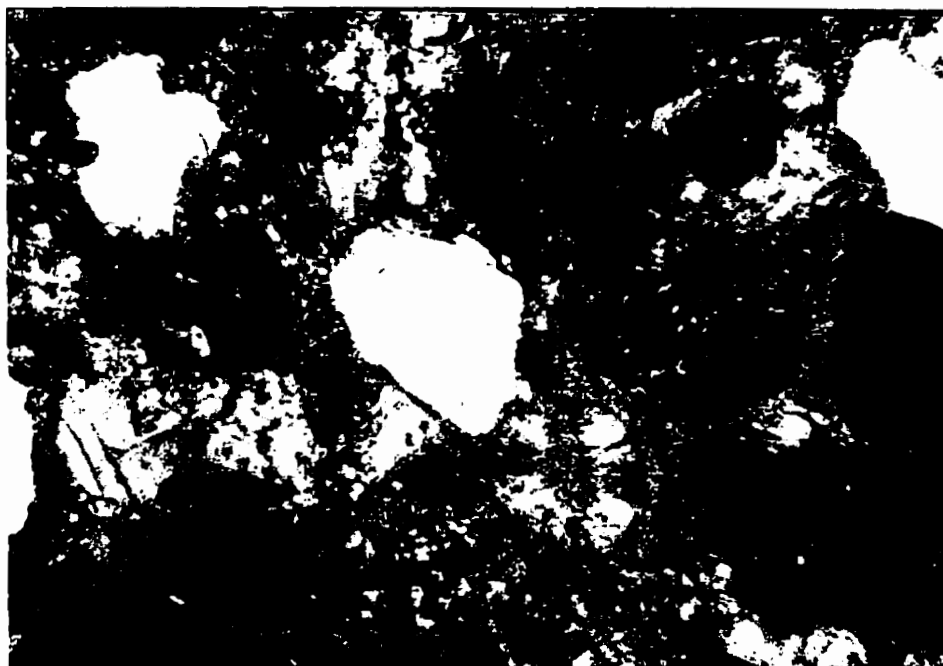


Figure 3.5: The transition between Lecho and Yacoraite shows increasing quantities of allochems, together with higher proportions of matrix. Also note the bigger size of grains relative to those of Fig. 3.4.. Note radial ooids. Sample 3, PTS, XPL, FOV = 2.15 millimetres.



Figure 3.6: A typical grainstone from lower Yacoraite Formation. Allochems are ooids, radial and concentric. Note compacted ooid in the left lower corner. Two types of cement are present: vestiges of fringe cement (F) and equigranular cement filling the pores (E). Sample 79, PTS, PPL, FOV = 0.85 millimetres.

The samples collected were studied and described using Folks and Dunham's carbonate classification (in Adams, 1984; Scholle, 1978). Staining (with Alizarin Red S and potassium ferricyanide; Dickson, 1965; Hitzman, 1999) was used to assist in the identification of the carbonate species. The copper-silver mineralization at Juramento is almost entirely hosted by this unit.

### 3.3.1 Grainstones

Generally, this rock type is composed of coated grains (ooids and oncoids; Figs. 3.6 and 3.7) and it is commonly partially to completely dolomitized. The oolites are large in size (from 400 to 1800  $\mu\text{m}$  in diameter). They are typically sparitic, with radial or concentric cortices of one layer (surface oolites) or more. In some cases, the cores contain microfossils or small terrigenous clasts. Some ooids are composite (i.e., have more than one nucleus) and other are cerebroidal (forming grapestones). Other allochems are intraclasts, fossils, peloids and lumps. Some macroscopic samples appear to be oolitic, but, on closer examination under the microscope, they are seen to be oncolites showing a series of concentric (commonly irregular) layers of algal growth. Intergranular and rim cementation (Fig. 3.8) are composed of sparite, microsparite and/or dolosparite. A meniscus-type cement is commonly present as well, suggesting frequent subaerial exposure of the sediments. Micrite is generally absent as a matrix, but micritized ostracods, pelecypods and gastropods are common (Fig. 3.9). Rims may be bored.

The grainstone porosity is normally high. It is typically fabric selective (Fig. 3.9), intraparticular and mouldic, together with minor, non-fabric selective fractures (Fig. 3.10) due to fault repetition and channels (following the classification of Choquette and Pray, 1970).

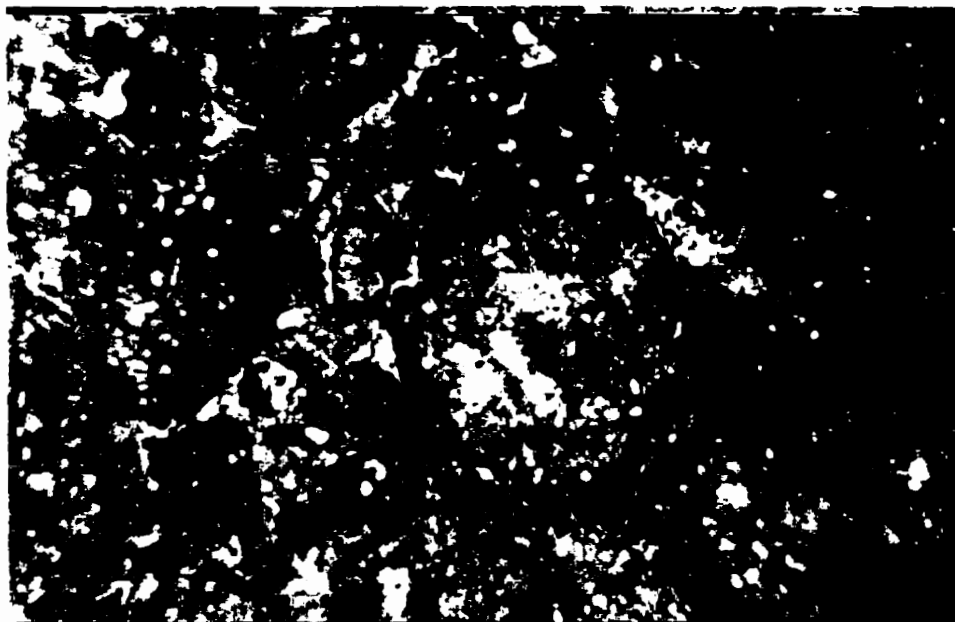


Figure 3.7: An oncolitic grainstone. Note pervasive dolomitization and micritization around oncolites. Ghosts of successive concretions are still visible, lower center. Sample 85, PTS, PPL, FOV = 5.4 millimetres.

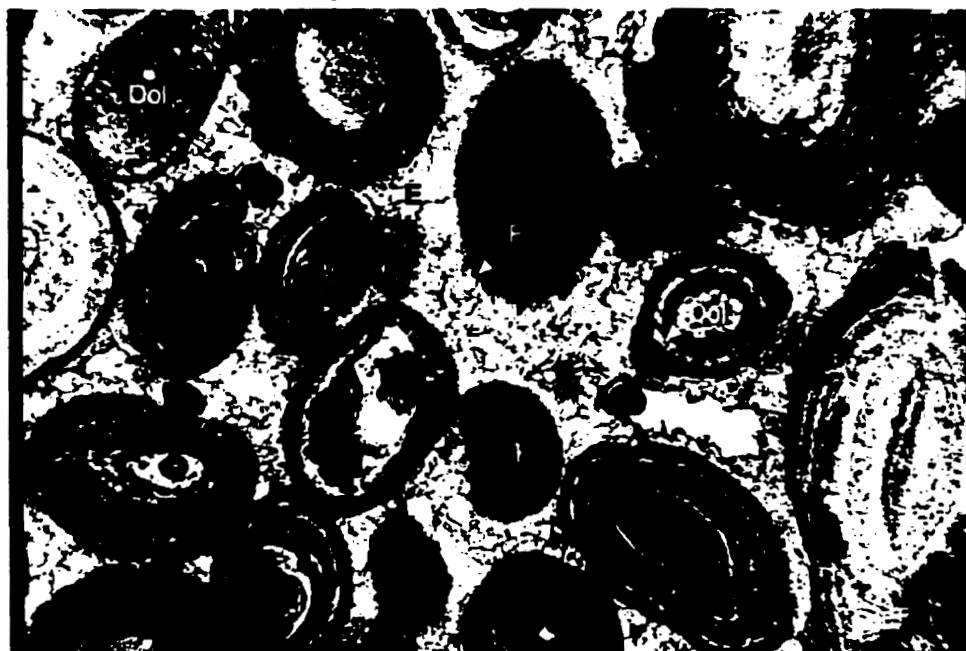


Figure 3.8: A grainstone from the Yacoraite Formation. Note the calcitic (rose) fringe cement relict (F), that predates the equant cement (E), slightly ferroan (light mauve). Note also dolomitized (Dol, not stained and blue-light blue) cortices in ooids and lumps, interpreted to be earlier than the equant cement. Sample 80, PTS, PPL, FOV = 2.15 millimetres.

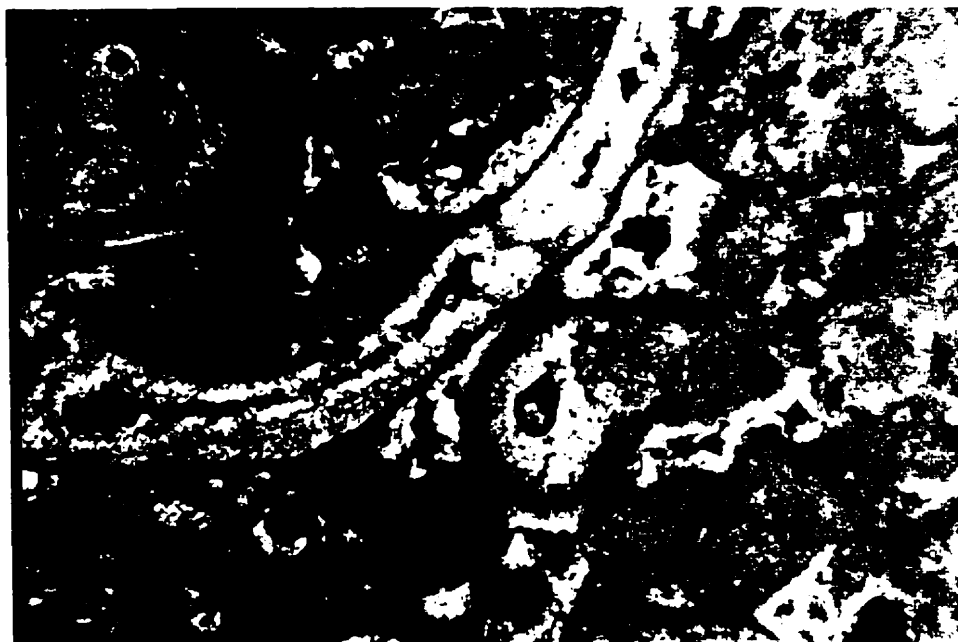


Figure 3.9: A micritized grainstone, with mouldic porosity and meniscus-type cement. Cement in voids is interpreted to be a second-generation cement. Sample JDH-08-4, PTS, PPL, FOV = 2.15 millimetres.



Figure 3.10: Grainstone showing secondary porosity created by fracturing. This fracturing is considered late because it crosscuts allochems and cement. Sample 13, PTS, PPL, FOV = 2.15 millimetres.

### 3.3.2 Packstones

In core samples, sediments corresponding to this carbonate texture are similar in appearance to that of the grainstone described above. However, in thin sections, the packstones present a matrix composed of micrite (Fig. 3.11) and allochems (small ooids and pellets; Fig. 3.12) situated between larger allochems (generally ooids up to ~2 mm in diameter). Micritic pellets and small ooids are approximately 200 micrometres or less in size and they are generally well sorted. The packstones also contain a variety of fossils such as ostracods, gasteropods, pelecypods, foraminifera, algae and phosphatic remnants, the last probably derived from fish. A few intraclasts are present too, commonly forming less than 2-3% of the total volume of the rock. They have irregular shapes and are typically greater than 2 millimetres in size. Some clasts represent eroded limestone characterized by a vadose cement formed under conditions of subaerial exposure. Where present, the cement is sparite, microsparite and/or dolomicrite and it is intergranular. The terrigenous fraction is minor. The porosity is mouldic, but lesser than that of grainstones.

### 3.3.3 Wackestones

The Yacoraite wackestones possess an abundant micritic and dolomicritic matrix, with patches of sparite (Fig. 3.13). Some isolated oolites show only one cortex layer (surface oolites); the cortices are concentric or radial. The porosity, represented only by vesicular, interparticular and fracture spaces, is poor.



Figure 3.11: A typical packstone from the Yacoraite Formation. The matrix is micrite and some allochems are micritized. This texture illustrates the extensive organic activity after deposition of sediments, but considered diagenetically early. Note stylolites and recrystallized matrix that probably occurred during late diagenesis of the rock. Sample 81, PTS, PPL, FOV = 2.15 millimetres.

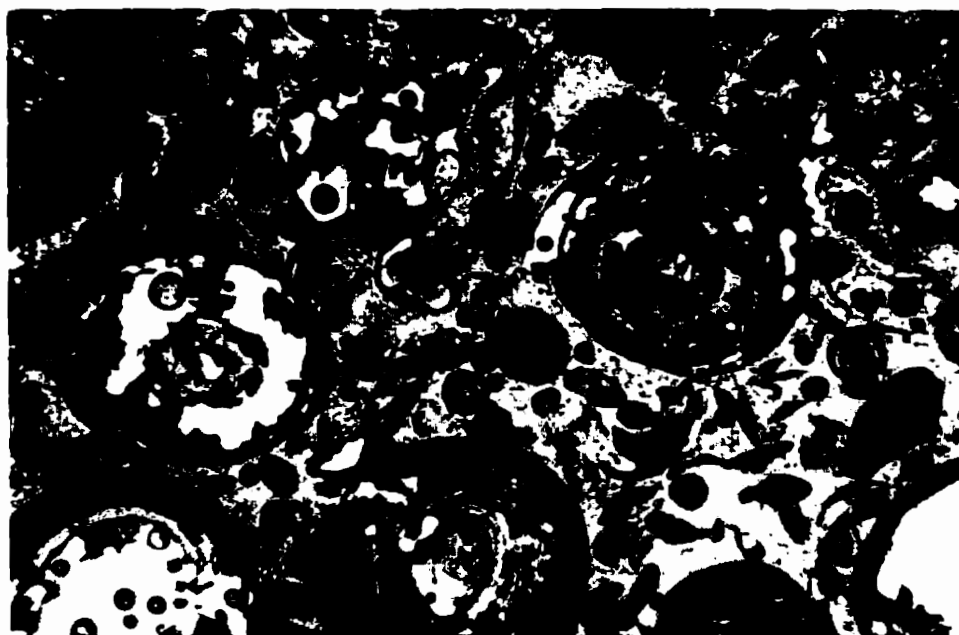


Figure 3.12: An oolitic packstone. The matrix consists of allochems and the cement is coarse-grained microspar. Note the secondary dissolution porosity (voids on allochems). Sample 5, PTS, PPL, FOV = 5.4 millimetres.

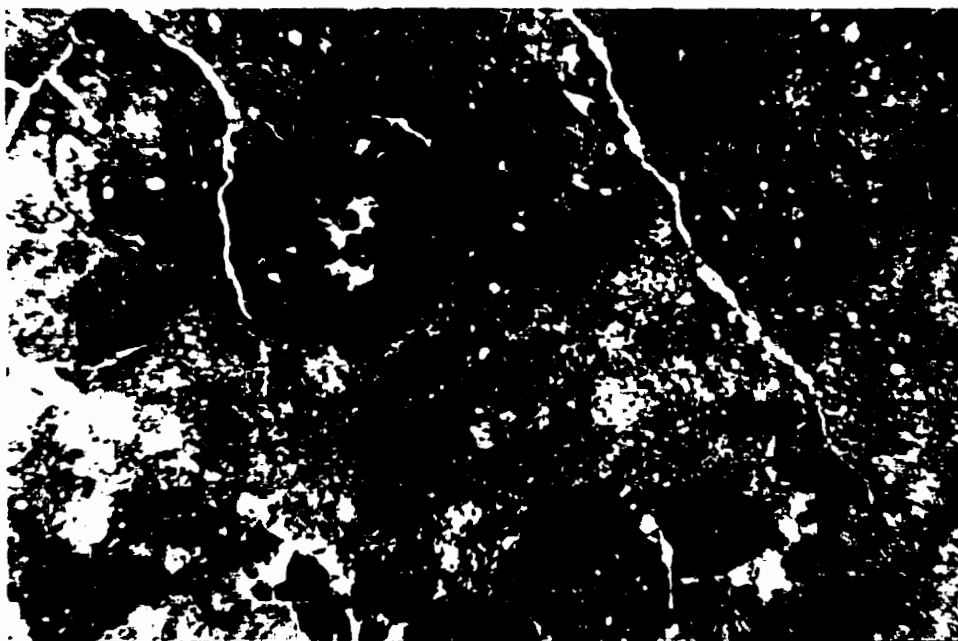


Figure 3.13: Dolomitized wackestone from the Yacoraite Formation. Allochems are interpreted to be oncolithes. Secondary porosity consists of dissolution voids and from fracturing. Sample 86, PTS, PPL, FOV = 5.4 millimetres.

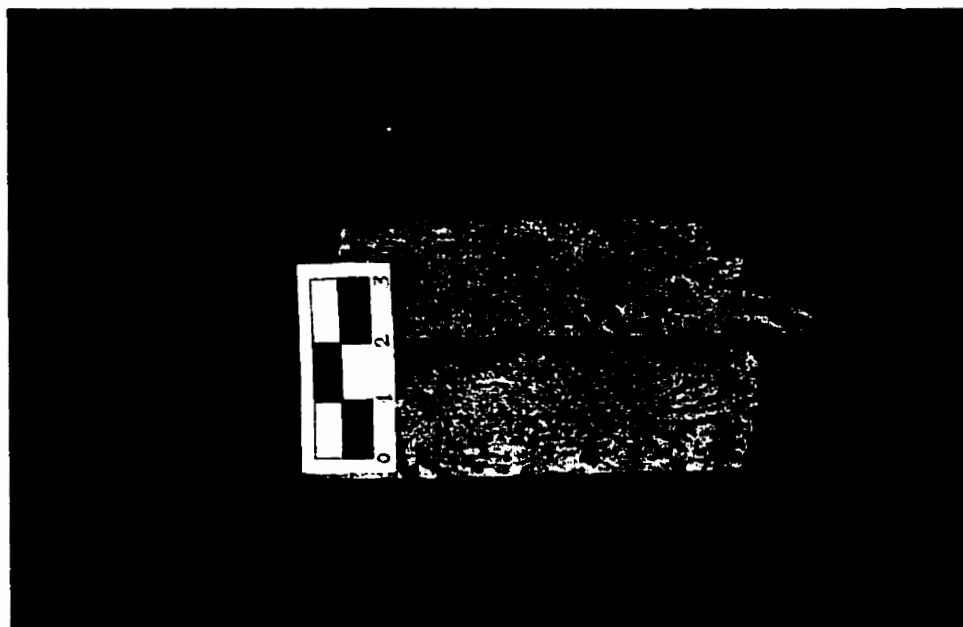


Figure 3.14: Drill hole samples of a burrowed mudstone. Note creamy colour due to dolomitization. Sample 27, CS. Scale is in centimetres.

### 3.3.4 Mudstones

In most cases, the Yacoraite mudstone is formed only of calcitic micrite and dolomicrite, thinly laminated or not. Bioturbation is commonly pervasive (Figs. 3.14 and 3.15). Fossils and allochems, mainly found in bioturbated mudstones, consist of gasteropods, pelloids, ostracods and algal fragments. The composition of the allochems and fossils is largely calcitic. The porosity is of a fenestral or vesicular type. In the case of bioturbated sections, the porosity would have been high.

### 3.3.5 Stromatolitic Boundstones

This facies of the Yacoraite Formation consists of calcareous or dolomitic laminations of algal origin, alternating with silty or sandy layers. At the macroscopic scale, alternating dark- and light-coloured laminae form gentle undulations representing the primary layered structure of stromatolites (Fig. 3.16) in which the active algae mats becomes covered by detritic grains that stick to the mat surface, and then another microcolony of algae grows through and develops on top of each silty or sandy lamination. After the buried colony dies and burial recrystallization occurs, the alternating terrigenous laminations and carbonate layers persist (Fig. 3.17). In some cases, the clastic layers include fossils (e.g., ostracods), oolites, pellets and other allochems. The porosity in the stromatolites is fenestral.

### 3.3.6 Siltstones

This sediment type is most abundant toward the upper parts of the Yacoraite Formation and in the transition into the overlying Tunal Formation. It is generally light- to dark-

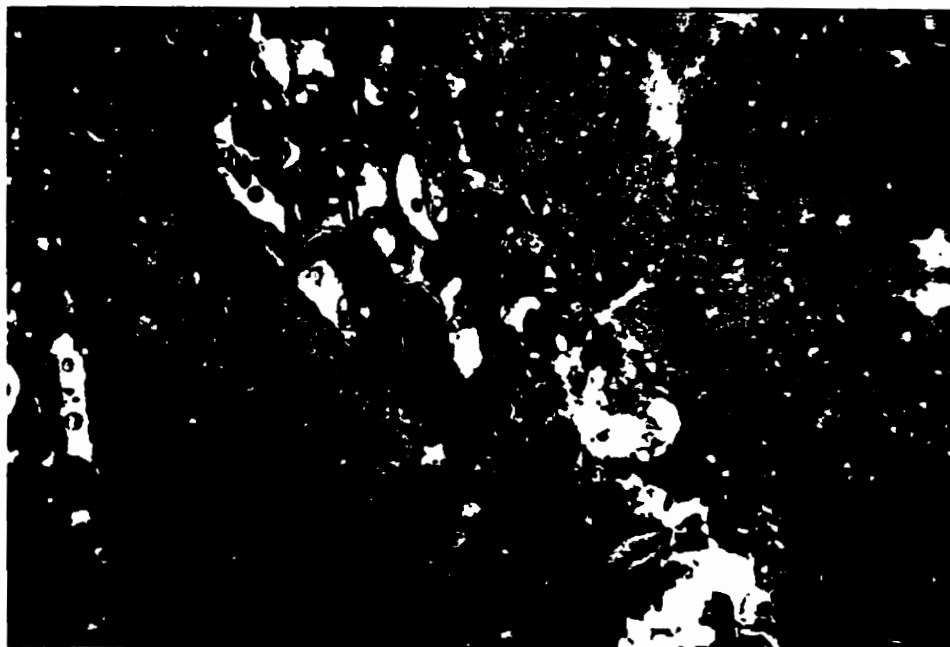


Figure 3.15: Detail of a burrow in a mudstone. Note that burrow is not dolomitized, suggesting that the dolomitization was complete by the time of boring of sediments by organisms. Sample 27, PTS, PPL, FOV = 5.4 millimetres.

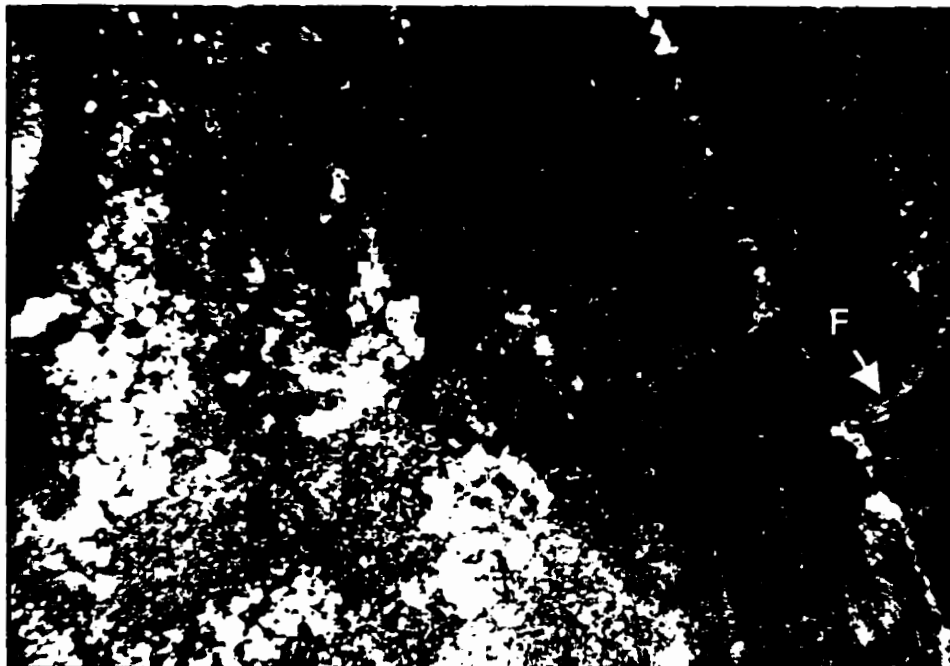


Figure 3.16: Stromatolitic boundstone. Calcitic laminae are highlighted by red staining and silicified fenestral porosity is filled with silica. Right upper corner shows unstained silicified laminations. The photomicrograph shows also late ferroan cement healing fractures(F). Sample 75, PTS, PPL, FOV = 5.4 millimetres.

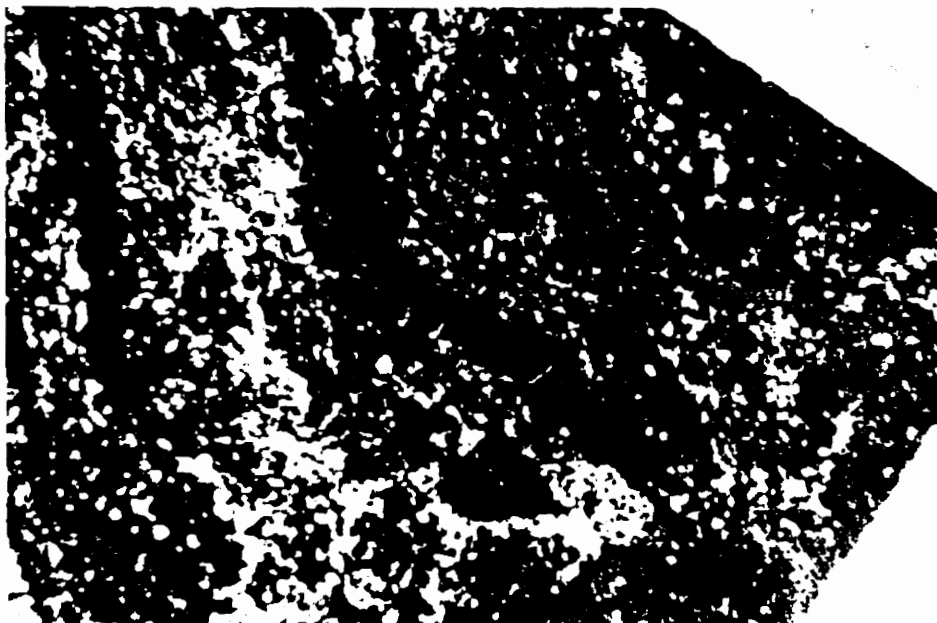


Figure 3.17: Fine calcareous laminations interlayered with calcareous siltstone and interpreted to be of algal origin. Sample 69, PTS, PPL, FOV = 14 millimetres.

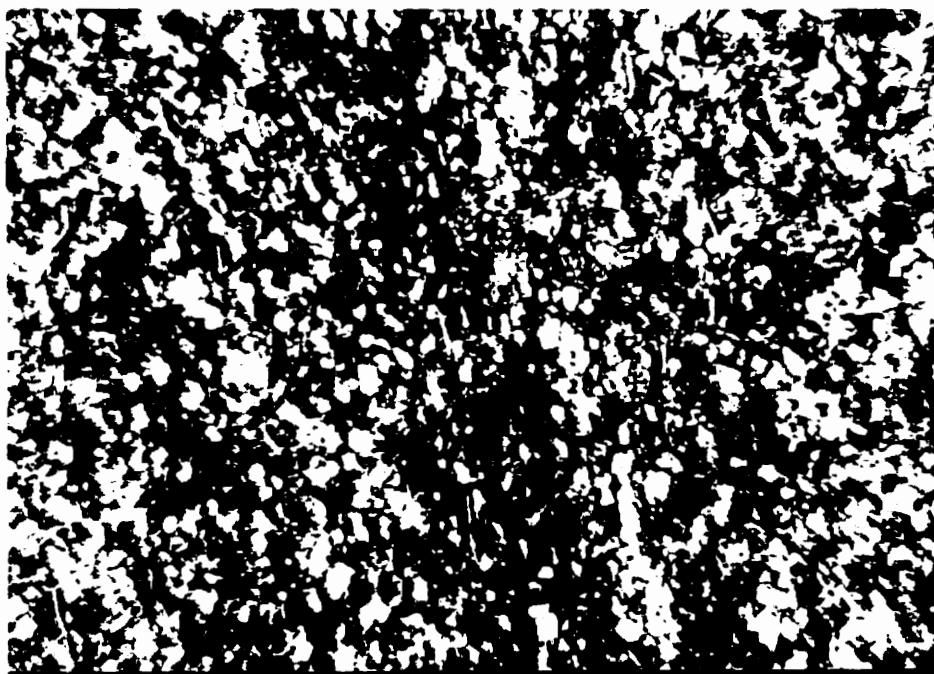


Figure 3.18: Siltstone with broad laminations and a calcareous-dolomitic matrix. The opaque minerals are pyrite grains. Sample JDH-8-11, PTS, XPL, FOV = 5.4 millimetres.

grey in colour, but it is more greenish than greyish in the Tunal Formation. The siltstone consists of thinly laminated silt with an argillic matrix and a calcareous cement (Figs. 3.18 and 3.19); the proportions of terrigenous grains, argillaceous matrix and calcareous cement are highly variable. The main component grain types are quartz and feldspar in the coarse silt size and phyllosilicates in the argillaceous matrix.

### 3.3.7 Marls

This fossiliferous clastic sediment type is most abundant toward the lower Yacoraite. It is composed of clays and a calcareous cement and the colour is dark-grey (Fig. 3.20). The porosity would have been low to effectively non-existent.

### 3.3.8 Intraformational Conglomerates

Intraformational conglomerates occur throughout the Yacoraite Formation (Fig. 3.21). This rock type is formed by clasts of 1 to 5 millimetres in size which are commonly angular or sub-angular. Clasts correspond to all types of sediments described in this section, including dolomitic mudstone. The matrix is composed of variable amounts of detrital quartz and feldspar grains of silt size, and the cement is dolomite and/or calcite.

## 3.4 Tunal Formation (upper Balbuena Subgroup)

The following brief descriptions are from megascopic observations made in the field by the author. The Tunal Formation consists of finely laminated, oolitic limestones with intercalations of stromatolites and fine-grained siliciclastics.

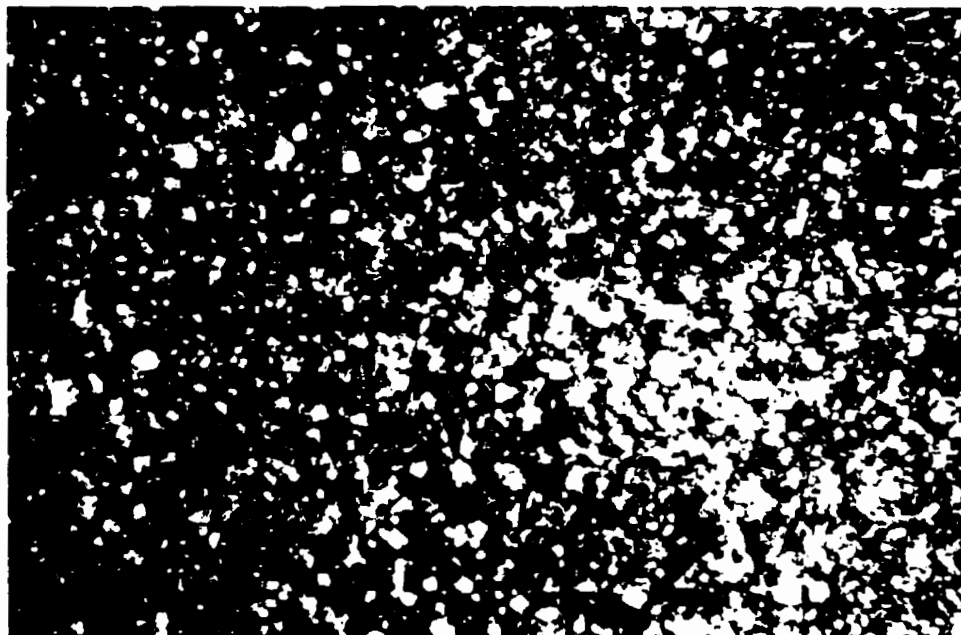


Figure 3.19: A typical siltstone from upper Yacoraite. Note the well-crystallized rhombohedrons of dolomite surrounded by authigenic silica (white-grey and opaque). Sample JDH-8-14, PTS, XPL, FOV = 2.15 millimetres.

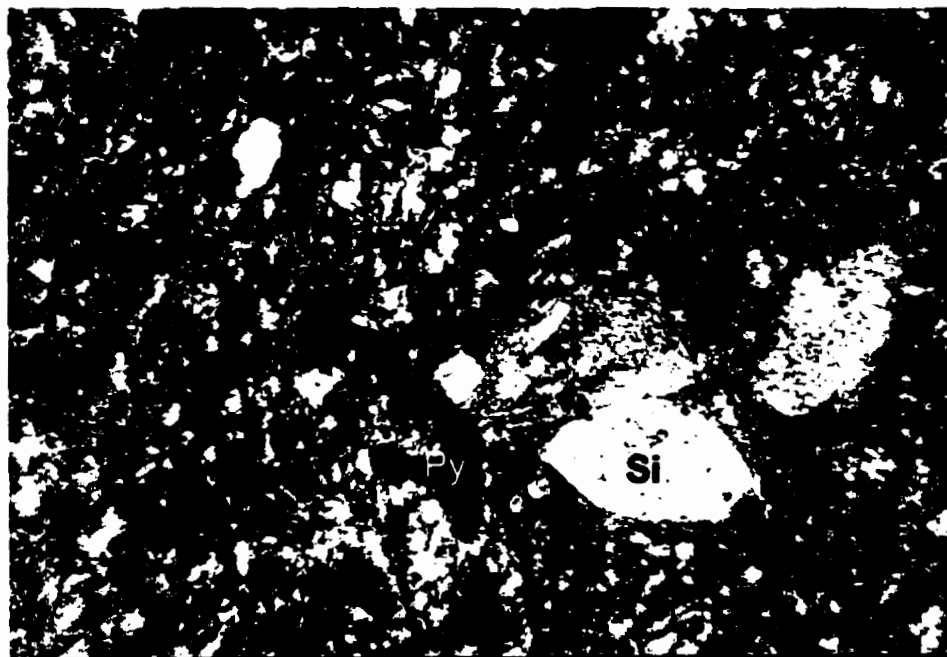


Figure 3.20: A marl. The matrix is more than 30% and there are few allochems (ostracods) distributed along interpreted laminations. One ostracod shows authigenic silica (Si) fill. Also note the presence of pyrite (Py) in the matrix, some very fine-grained. Sample 6, PTS, PPL, FOV= 0.85 millimetres.

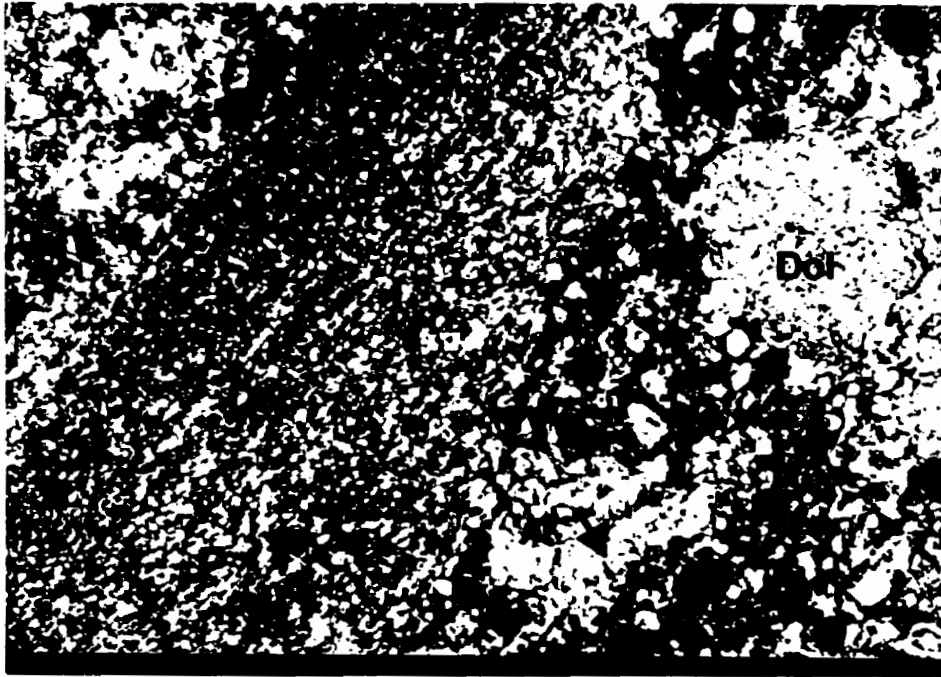


Figure 3.21: An intraclastic conglomerate. The figure shows dolomitized siltstone and dolomitized mudstone clasts (Dol.). Dolomite present in these clasts is fine and its texture contrasts with the texture of the dolomite present in the matrix (arrow). This observation suggests a very early dolomitization, prior to any consolidation of sediments and later erosion and transport to the sedimentation site. Note also the presence of amorphous silica (probably opal) in the matrix (appears opaque), indicating a late emplacement. Sample 71, PTS, XPL, FOV = 5.4 millimetres.

The most notable characteristic of this unit is its greenish-yellow colour which contrasts with the grey to orange-yellow colour of the Yacoraite Formation (see section 3.3).

### **3.5 Santa Barbara Subgroup**

These sediments are characterized by reddish to orange-coloured calcitic claystones and siltstones exhibiting fine parallel laminations. Such laminations, observed in the first metres downward in DDH 25, lie with parallel conformity over the Tunal Formation sediments. These reddish strata are interpreted to be equivalent to the Mealla Formation (Espisúa and Amengual, 1983). They can also be observed to the east of trench B on Cerro del Plomo.

## **CHAPTER 4**

### **PETROGRAPHY OF THE YACORAITE FORMATION**

After familiarization with the general geology and the main stratigraphic units of the study region in the previous chapters, in this chapter we provide descriptions of the minerals and particular textures of the many facies of the Yacoraite Formation which hosts the Juramento mineralization, with the objective of determining the relationship between processes affecting this host rock.

#### **4.1 Calcite**

Calcite is one of the most abundant minerals in the Yacoraite Formation. It is present as a cement, as a matrix and as the essential rock-forming mineral of most allochems. Using staining techniques (see Appendix 1), it is possible to detect two types of calcite: red-stained calcite of low iron content, and blue-mauve-stained calcite of high iron content.

As a cement, calcite is present as sparite consisting of single idiomorphic to subidiomorphic calcite crystals of up to 100 micrometres in size. This sparite or equant cement fills the interparticular primary porosity (Fig. 4.1) and vadose porosity (Fig. 4.2). Equant sparitic cement occupies the mouldic porosity created by dissolution of less stable forms of calcium carbonate, such as originally aragonitic gasteropod shells (Fig. 3.9). Sparitic calcite heals (totally or partially) the open spaces in fractures that transect

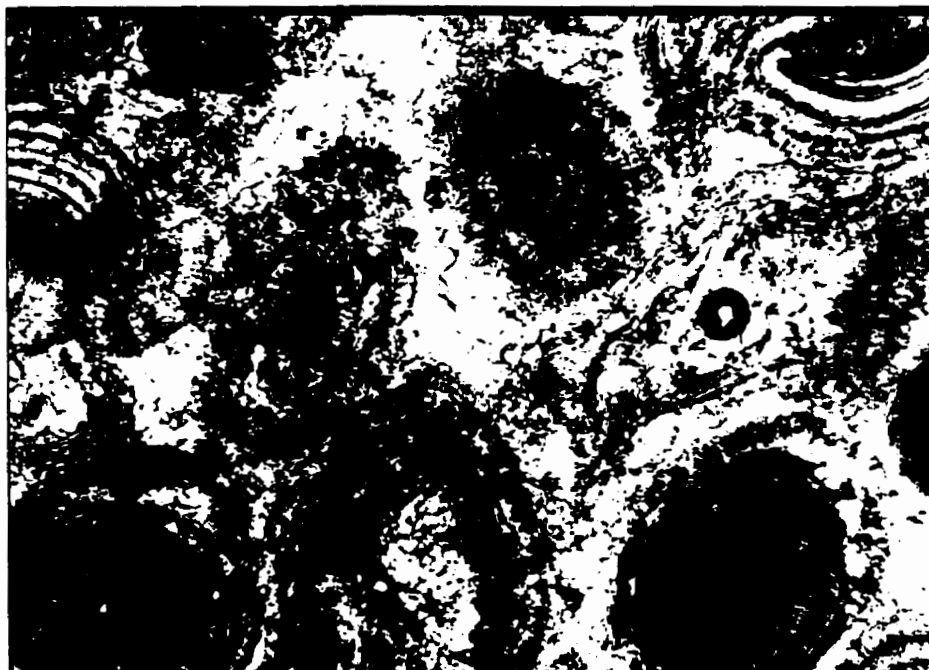


Figure 4.1: A grainstone with interparticulate equant sparitic cement healing primary porosity. Note spalled cortices that were filled with sparite, flattened ooids and equant cement that indicate that compaction occurred in a slightly cemented sediment. Sample 79, PTS, PPL, FOV = 2.15 millimetres.



Figure 4.2: A grainstone with vadose porosity healed by equant sparite (rose); getting more ferroan towards the center (mauve). Note that the vadose cement is fine-grained texture, non stained, probably after micrite. Dolomitization is interpreted to be earlier than the equant cement, but later than micritization and dissolution that might have taken place in the vadose zone. Sample 80, PTS, PPL, FOV = 0.85 millimetre.

allochems matrix and cement (Fig. 4.3).

Another type of calcitic cement forms vestiges of fringe cement around various allochems. Fringe cement is formed by needle-like calcite crystals arranged perpendicular to the allochems (Fig. 4.4).

Microsparitic cement is also observed in a few samples. It consists of xenomorphic to subidiomorphic calcite crystals 10 to 20 micrometres in size filling secondary porosity (Fig. 4.5). Micrite is also formed of small calcite crystals, less than 5 micrometres in size. In the matrix, calcitic micrite was observed to support allochems and detrital grains (Figs. 3.11 and 4.6). Microspar was also found to constitute the matrix; in such cases, the texture suggests recrystallization of micrite (Fig. 4.7).

Calcite is the major constituent in allochems. It is present in allochems as the essential material of pellets and lumps. In the cortices of ooids, it is present in two forms: as radial fibers up to 15 micrometres in length, and as concentric layers of calcareous mud encrusting the nuclei (Figs. 3.6 and 3.8). Despite partial recrystallization of the ooids, in many cases the radial disposition of the previous thin calcite crystals is retained (Fig. 3.5).

## **4.2 Dolomite**

This carbonate is also very common, although it appears to be subordinate in abundance to calcite. It replaces calcitic sediments to various degrees, and in some cases it completely replaces the calcareous sediment to form a dolostone. Cupriferous mineralization is not confined to dolomitized areas, as may be the case in other ore deposit types (e.g., Mississippi Valley-type lead-zinc mineralization).

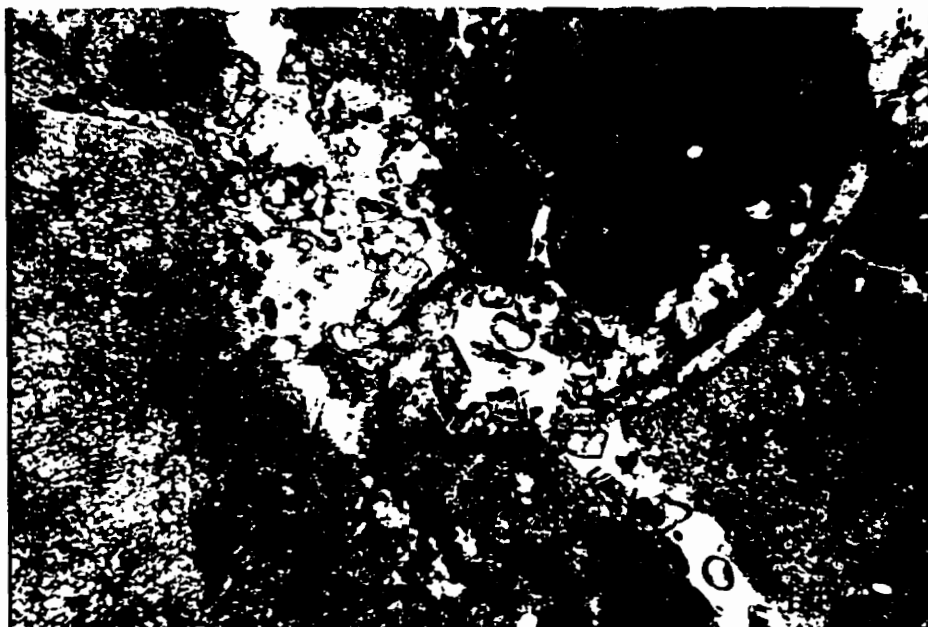


Figure 4.3: Fracture in a dolomitic wackestone. The fracture is healed by late ferroan calcite (mauve) that occupies mouldic porosity after a dissolved shell. Sample 84, PTS, PPL, FOV = 2.15 millimetres.

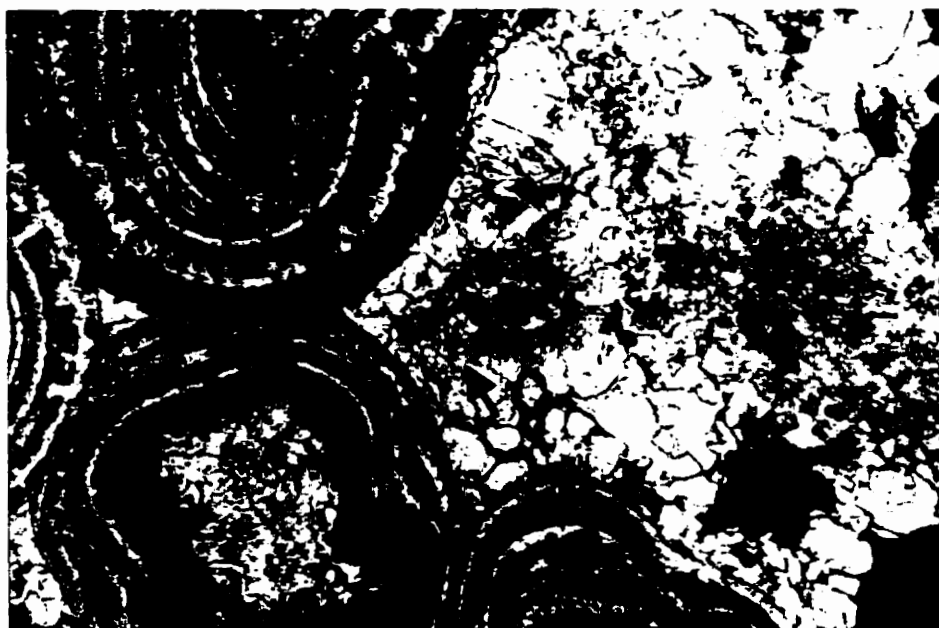


Figure 4.4: Relict of fringe cement around a small ooid (arrow), surrounded by slightly ferroan equant spar cement. Sample 80, PTS, PPL, FOV = 0.87 millimetres.

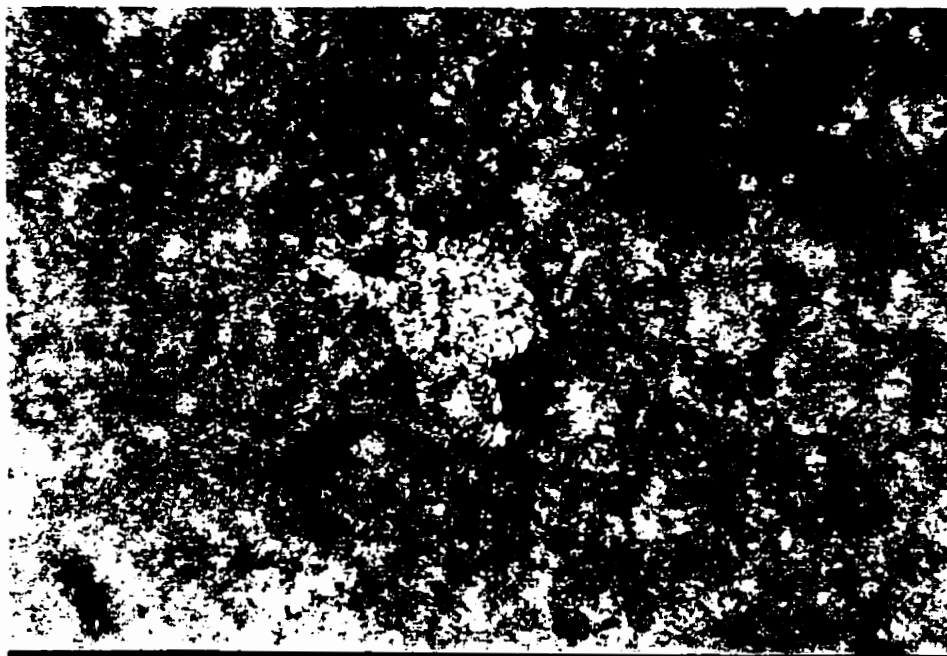


Figure 4.5: Microsparitic cement filling secondary porosity (centre) created by dissolution in a mudstone. Sample JDH-8-10, PTS, XPL, FOV = 0.34 millimetres.

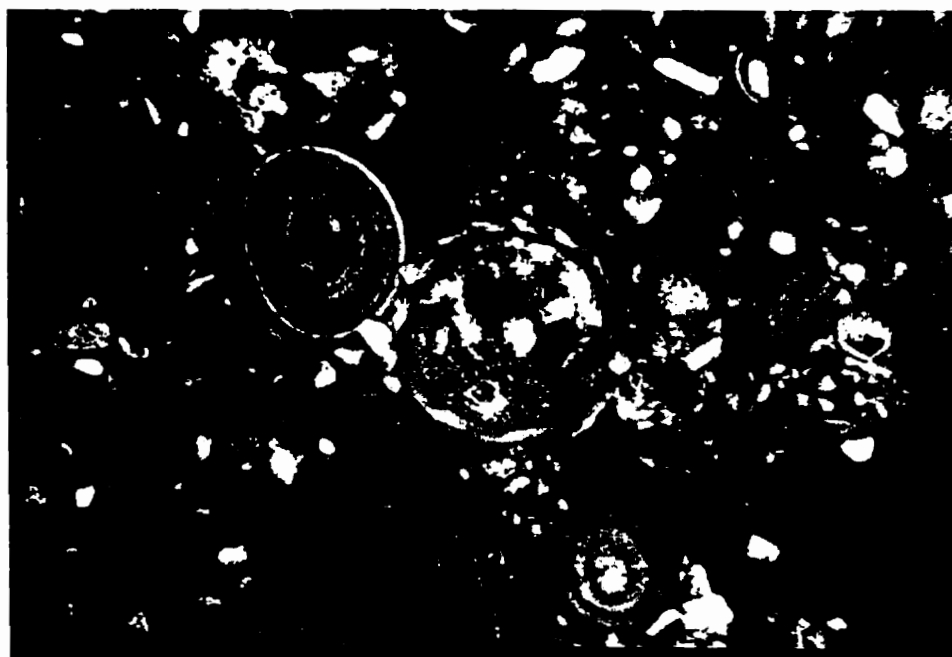


Figure 4.6: Greywacke showing micritic matrix supporting detrital grains and a few allochems. Note the presence of a fossil interpreted as being a charophyte (centre). Sample JDH-8-12, PTS, XPL, FOV = 5.4 millimetres.



Figure 4.7: Microspar (M) as matrix in a sediment interpreted as wackestone. Note the patches of microspar inside allochems. Note also the preserved secondary porosity in the stylolite (S), still open, and the presence of sphalerite(sph). Sample 12, PTS, PPL, FOV=2.15 millimetres.

The presence of dolomite is easily detected in hand specimens by the whitish colour of the rock compared to the dark-grey of calcareous carbonates. Further confirmation of the carbonate type may be made by staining with the combined staining formula (see Appendix 1): the whitish colour of the dolomitic rock turns to a turquoise colour. Upon closer examination in thin section, the staining is found to be inhomogeneous, with some areas showing no stain, indicating a dolomite with an insignificant iron content, whereas other portions are blue-stained, indicating a ferroan dolomite (see Dickson, 1966; Hitzman, 1999).

During the study of thin sections, two main types of dolomite were recognized: fine-grained dolomite and coarse-grained dolomite. Fine-grained dolomite is composed of xenomorphic to subidiomorphic crystals of dolomite 5 to 10 micrometres in size (Fig. 4.8), whereas coarse-grained dolomite is composed of euhedral crystals of dolomite of approximate 50 micrometres size. Under closer examination, fine-grained dolomite inclusions are seen within coarse-grained dolomite crystals (Fig. 4.9). This texture suggests that the coarse-grained dolomite resulted from recrystallization of fine-grained dolomite.

Fine-grained sediments (e.g., mudstones, wackestones, boundstones and siltstones) seem to have experienced greater degrees of dolomitization than coarse-grained sediments. Dolomite appears to be particularly abundant in the detritic sections of the Middle and Upper Yacoraite, where, among other textures, it occurs as isolated rhombohedra in the cement and matrix (Figs. 3.18 and 3.19). To variable degrees, dolomite also replaces the calcite in cements, matrices and allochems in most sedimentary facies throughout the stratigraphic column. As such, dolomite is also present in many horizons of oolitic grainstones, packstones, wackestones, mudstones and stromatolites in the Lower and Middle Yacoraite on Cerro del Plomo and Cerro del Cobre.

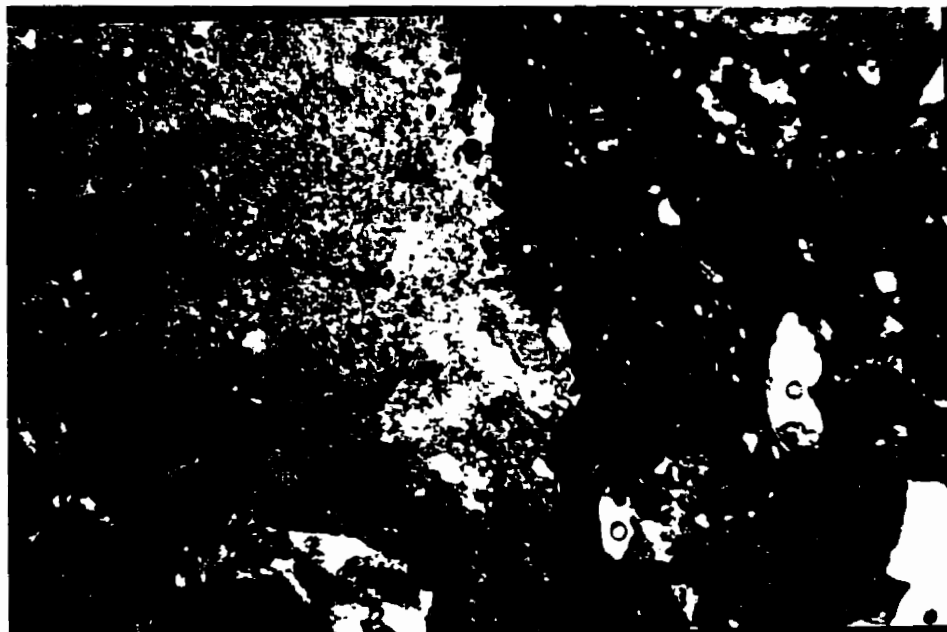


Figure 4.8: Fine-grained dolomite in a bioturbated mudstone, with a massive texture showing patches of slightly coarser grained dolomite. Note the accumulation of detritals, shells and carbonaceous matter in the bioturbated areas (left portion of view). Sample 27, PTS, PPL, FOV = 5.4 millimetres.

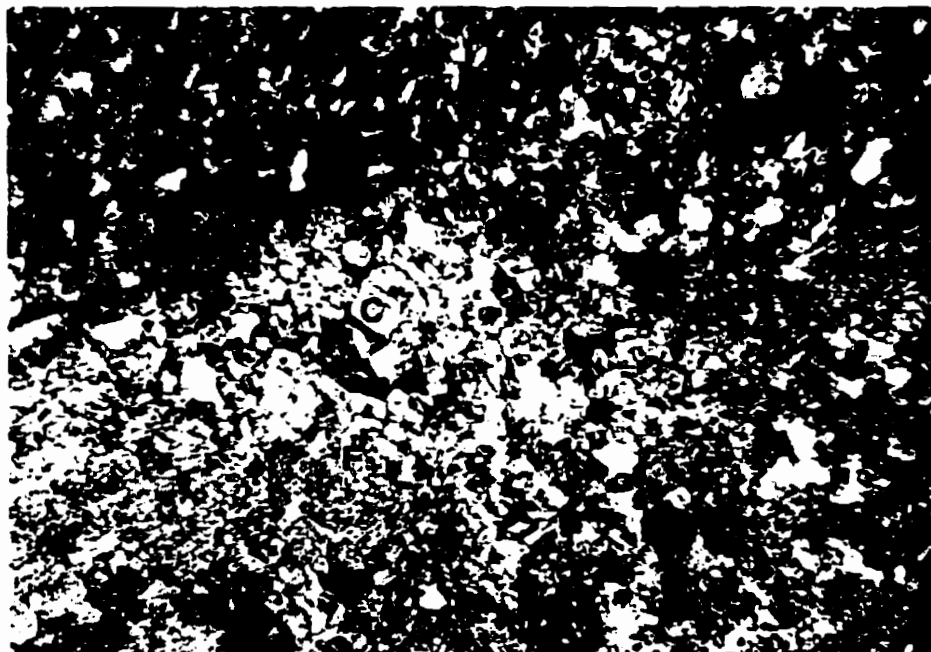


Figure 4.9: Well-crystallized rhombohedrons of coarse-grained dolomite. Note that coarse-grained dolomite (C) is intergrown with fine-grained dolomite (F), suggesting that coarse-grained dolomite is the result of the recrystallization of fine-grained dolomite. Note that the ferroan calcite (mauve) occupies intercrystalline porosity and postdates the coarse-grained dolomite. Sample 71, PTS, PPL, FOV = 2.15 millimetres.

Dolomitic mud and dolomitized siltstone clasts were found in intraclastic conglomerates (Fig. 3.21). In one sample, the pyritic aggregates occupy intergranular spaces and include calcitic and partially dolomitized allochems (Fig. 4.10). More distant from the margins of this pyritic aggregate, the allochems are dolomitized and their intergranular spaces are filled with authigenic microquartz and megaquartz. Also, in a few siltstones and fine-grained carbonate samples, dolomite rhombohedra in siltstones are surrounded by a silicified cement and matrix (Fig. 4.11). This observation suggests that dolomitization occurred early, postdated pyrite formation and took place before silicification. It also shows that dolomitized sediments were affected by late diagenetic processes such as would occur during deep burial.

### 4.3 Silica

Angular to subangular detrital grains of quartz are present in the Yacoraite Formation in almost all sedimentary facies. The size of such grains is variable, ranging from fine- to coarse-sand sizes in the Lower Yacoraite transition (Fig. 3.5), to medium- to coarse-silt sizes in the Upper Yacoraite (Figs. 3.18 and 3.19). Detrital quartz grains form primary sedimentary textures, such as fine laminations in siltstones. Also, vadose silt-size quartz grains fill mudcracks and burrows in some cases.

Authigenic silica is present as single idiomorphic crystals, as overgrowths on detrital grains and as aggregates of equigranular and fibrous quartz (following the classification of Hesse, 1990).

Single authigenic crystals are typically idiomorphic (well-developed prisms), with individual coarse grains attaining 100 micrometres in size and commonly containing carbonate inclusions. These single crystals are present in intergranular pores around

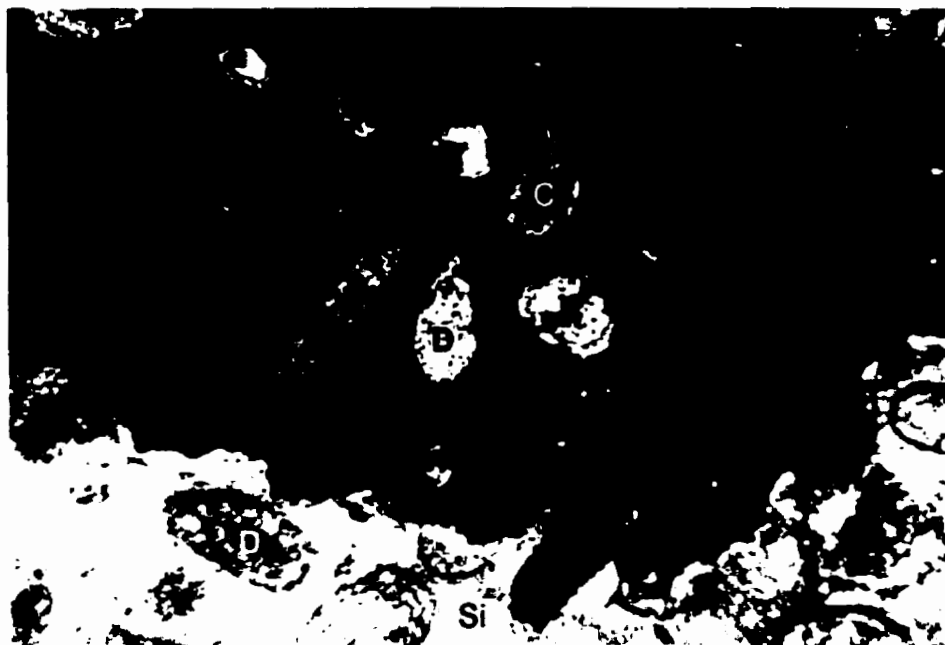


Figure 4.10: Dolomitized ooids included in a pyritic aggregate (dark). Note that towards the interior of the aggregate, a few allochems show calcitic composition with dolomitic rims (C). Outside the pyritic aggregate the dolomitized allochems (D) are surrounded by silica cement (Si). This texture suggests that dolomitization predates silicification. Sample 70, PTS, PPL, FOV = 5.4 millimetres.

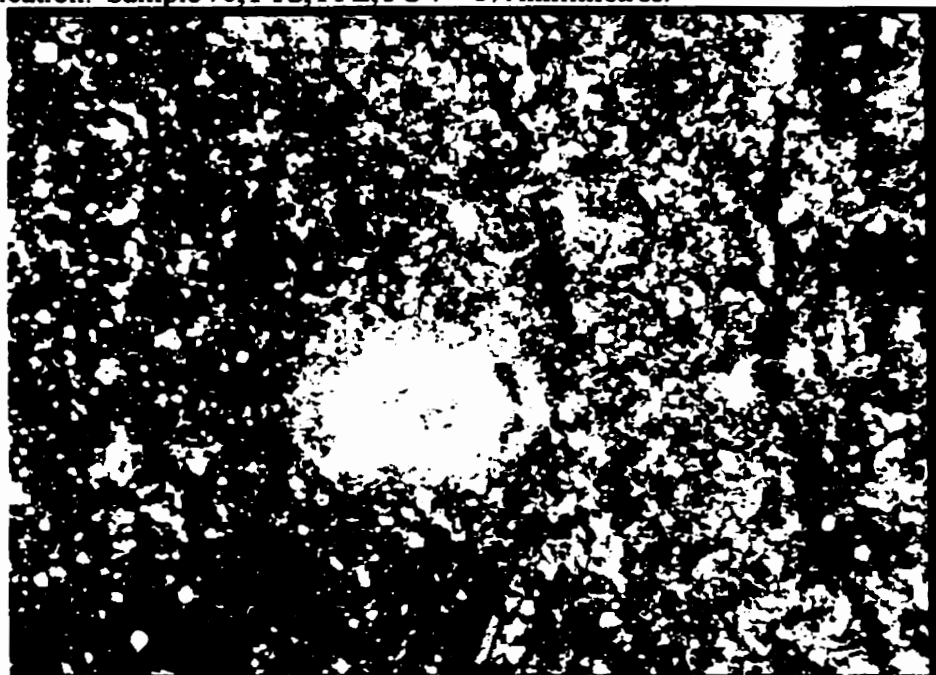


Figure 4.11: Dolomitized wackestone showing euhedral dolomite (light brown) floating in a silica (dark grey), suggesting dolomitization previous to silicification. Note the dolomitic ghost of a silicified ooid. Sample 11, PTS, XPL, FOV = 2.15 millimetres.

ooids and in open spaces (voids) (Fig. 4.12); they are also concentrated with other insoluble material (organic matter, sulphides, etc.) in stylolites (Fig. 4.13). Rims of quartz and individual quartz crystals are very common as overgrowths on detrital grains (Figs. 4.14 and 4.15).

As equigranular aggregates, microcrystalline silica is present as replacement patches in the matrix and cements of various fine-grained sediments (Fig. 4.11). The replacement patches consist of aggregates of opal and more ordered forms of silica, such as quartz grains less than 5 micrometres in size. Microcrystalline quartz aggregates replace the nuclei and cortices in ooids (Fig. 4.16) and fill empty shells (Fig. 3.20) and secondary porosity (Fig. 4.17). The aggregates are composed of xenomorphic to subidiomorphic grains, slightly greater in size than the aggregates of opal, with individual grains ranging between 5 and 20 micrometres in size. Megaquartz is present as a cement and has a mosaic fabric similar to equant sparitic cements (Fig. 4.18). Typically, the quartz grains are between 20 and 40 micrometers in size and display larger grain sizes toward the centres of interparticular spaces. Fibrous and microcrystalline quartz was also seen to replace gypsum (Figs. 4.19 and 4.20).

#### **4.4 Pyrite**

This sulphide is common in all lithologies of the Yacoraite Formation. There is no apparent stratigraphic control over its abundance, other than an association with organic matter. Two textural types are recognized: (1) very fine-grained disseminated pyrite and clusters of very fine-grained pyrite (including framboidal pyrite), and (2) coarse-grained euhedral pyrite.

Very fine-grained pyrite ranges from less than 5 micrometres to approximately 15

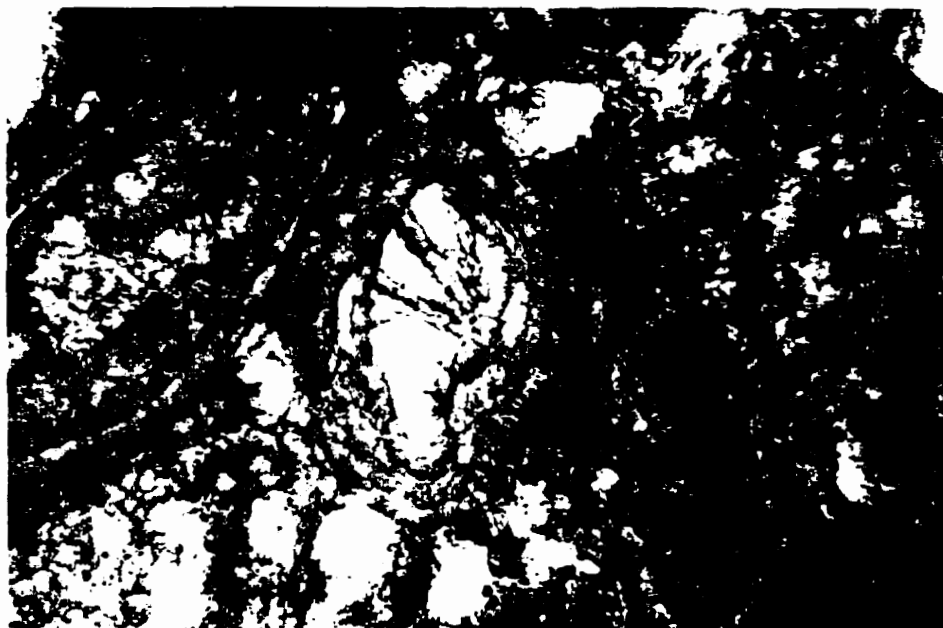


Figure 4.12: Dolomitized oolitic grainstone, with preserved secondary porosity; showing authigenic quartz needles growing into the void. Sample 14, PTS, PPL, FOV = 0.85 millimetre.



Figure 4.13: Stylolite developed in the interface between two sediments and showing concentration of authigenic quartz and insoluble material such as organic matter and sulfides. Note the contrast between the concentrations of quartz in the sediments and in the stylolite. Sample 34, PTS, PPL, FOV = 2.15 millimetres.



Figure 4.14: Authigenic quartz rim around a detrital quartz grain noticeable by the fluid inclusions around the former grain. Sample 26, PTS, PPL, FOV = 0.85 millimetre.



Figure 4.15: Authigenic quartz rim around detrital quartz displayed in radial form around the detritic grain. Note the presence of pyrite (opaque) in the layers of a cortice and a sulphide grain surrounded by authigenic quartz healing porosity (qtz). Sample 21, PTS, XPL, FOV = 0.85 millimetre.

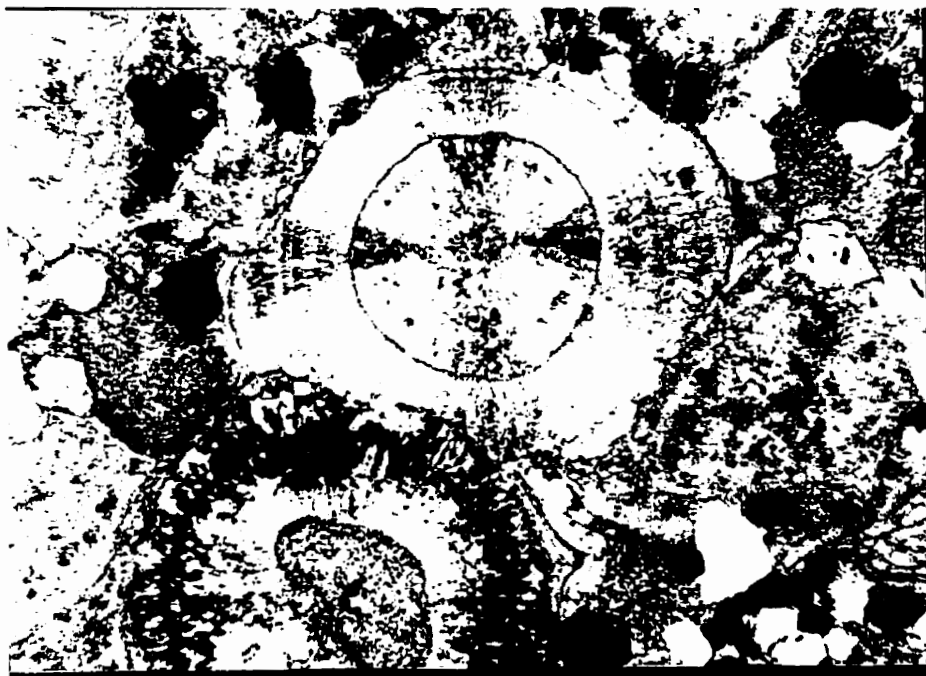


Figure 4.16: Oolitic grainstone showing radial cortice of ooids replaced by authigenic quartz preserving the radial arrangement, suggesting that replacement occurred early before transformation of the rim to more stable forms of calcite. Note the deformation due to packing and the pressure solution contact of ooids. Note also the presence of euhedral quartz around ooids; the texture suggests that the ooids resisted compaction and were present before burial. Sample JTH-4, PTS, XPL, FOV = 2.15 millimetres.



Figure 4.17: Microcrystalline quartz healing secondary porosity created by dissolution of the core of an ooid. The figure shows also a late fracture healed by sparitic cement, probably ferroan. Sample JDH-8-11, PTS, XPL, FOV = 0.85 millimetre.

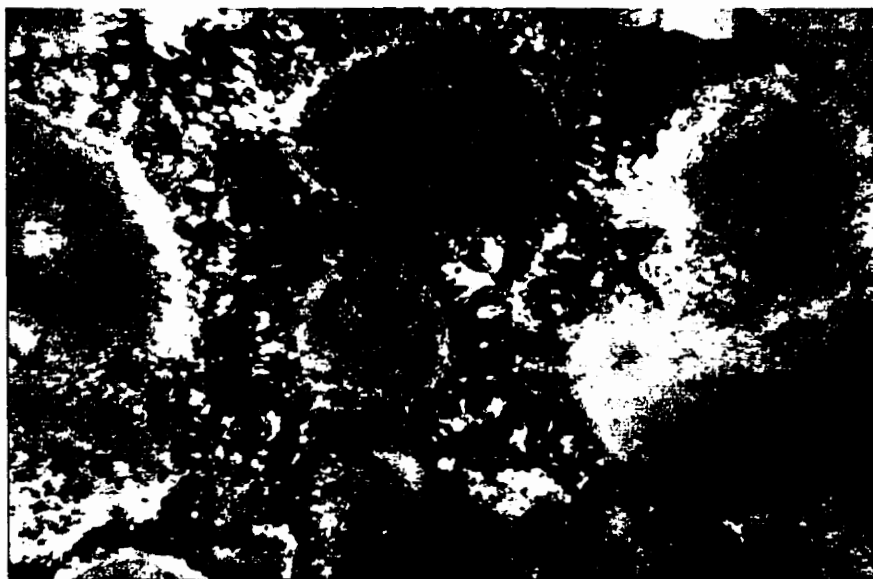


Figure 4.18: Megaquartz healing interparticular porosity, increasing in size towards the centre of the intergranular space. Note the presence of very fine-grained pyrite included in the ooids (arrows). Sample 70, PTS, XPL, FOV = 0.85 millimetre.

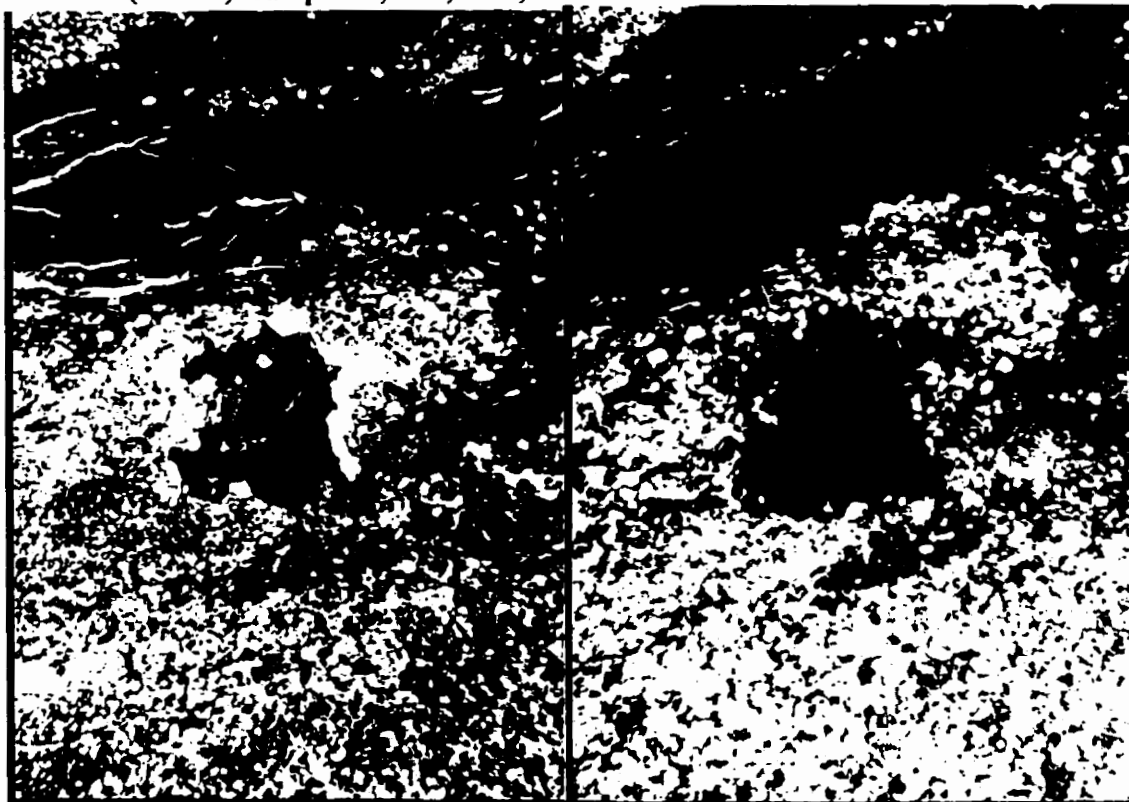


Figure 4.19: Dolomitic siltstone showing fibrous microquartz displayed as a rim in a dissolution cavity and filled towards the centre by less-ordered forms of silica, probably opal. This texture is interpreted as the result of the replacement of gypsum nodules by silica. Sample 67, PTS, PPL (left) and XPL(right), FOV = 5.4 millimetres.

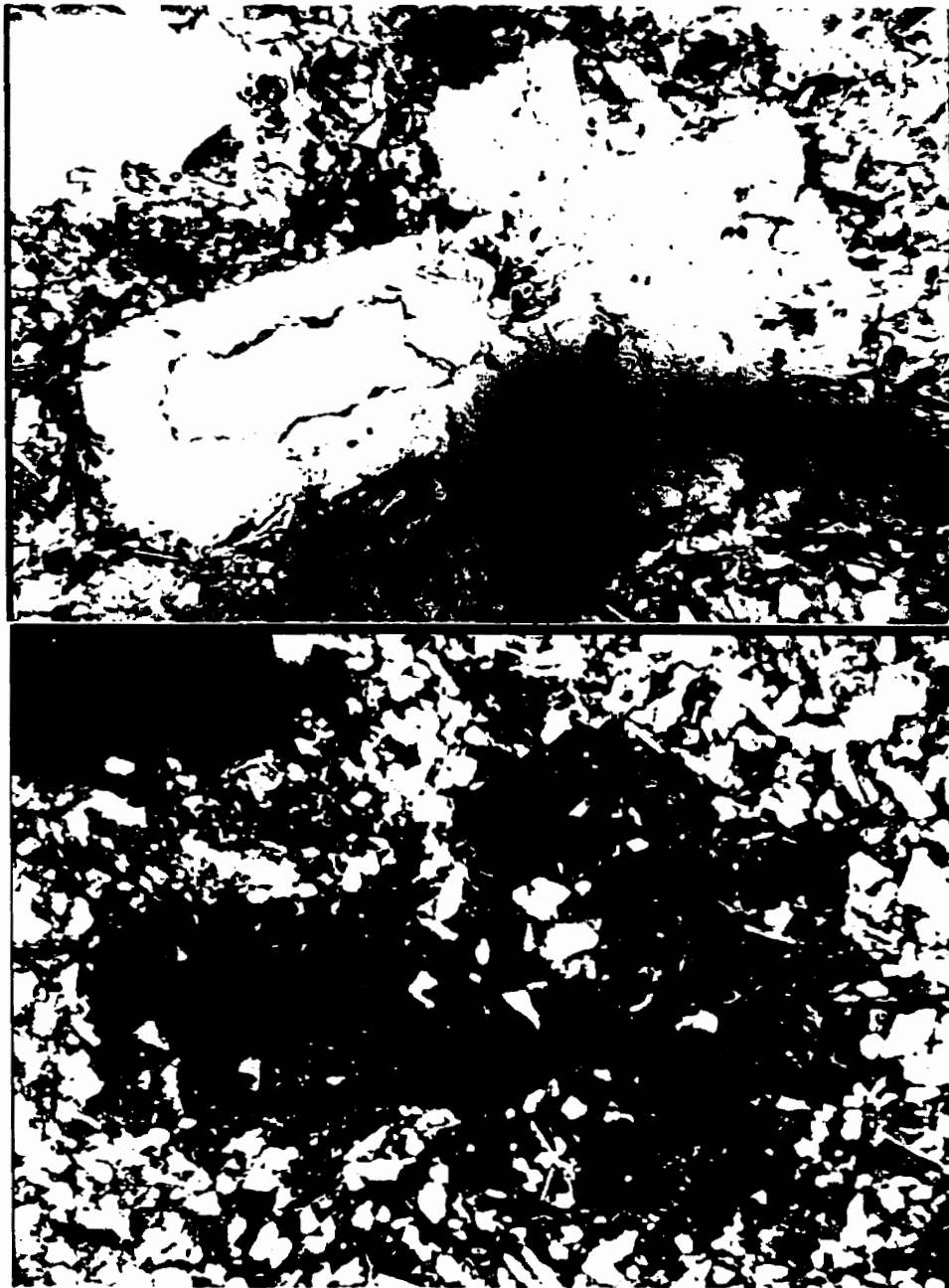


Figure 4.20: Siltstone showing fibrous and microcrystalline quartz as a rim, replacing a mould of an evaporitic mineral, probably gypsum. Sample 68, PTS, PPL (upper), XPL (lower), FOV = 2.15 millimetres.

micrometres in size (Fig. 4.21) and consists for the most part of disseminated euhedral grains. This type of pyrite is also seen as clusters, including spherical aggregates identified as framboidal pyrite (Fig. 4.22). This pyrite is invariably associated with carbonaceous matter. Presumably the organic matter encouraged anaerobic sulphate-reducing bacteria to produce the sulphide now found in very fine-grained pyrite (Trudinger et al., 1985).

Some ooids with multiple cortex layers have very fine-grained pyrite between their layers (Fig. 4.23). This texture indicates the entrapment of organic matter between layers of the cortex and the creation of local reducing conditions. The preservation of reducing conditions by the overgrowth of the next cortex layer would assure a reducing microenvironment despite possibly agitated and oxygenated waters in the immediate surroundings. Sulphate-reducing bacteria feeding on the organic matter could then produce the sulphide to form interlayer pyrite.

Very fine-grained pyrite also occurs between layers in oncoids, a sediment formed by algae encrustations. In such case, organic matter was again available for local bacterial reduction of sulphate. It is also possible to see pyrite in the nucleus of ooids that include carbonaceous mud (former algae) (Fig. 4.21).

Pyrite is also present in a very fine-grained habit around ghosts of recrystallized shells or allochems: some such ghosts are recognizable only by a thin mould of micrite (micritization includes the phenomena of algae boring and burrowing) and in micritized sediments before the arrival of sparry cement (Fig. 4.24). In some carbonaceous siltstones, very fine-grained pyrite forms up to 30 or 40% of the rock, with pyrite concentrated in bands along bedding planes. This pyrite is also present within thin laminations of algal origin, as in stromatolites occupying fenestral porosity (Fig. 4.25). This lithology is particularly known for the development of framboidal pyrite. It is also

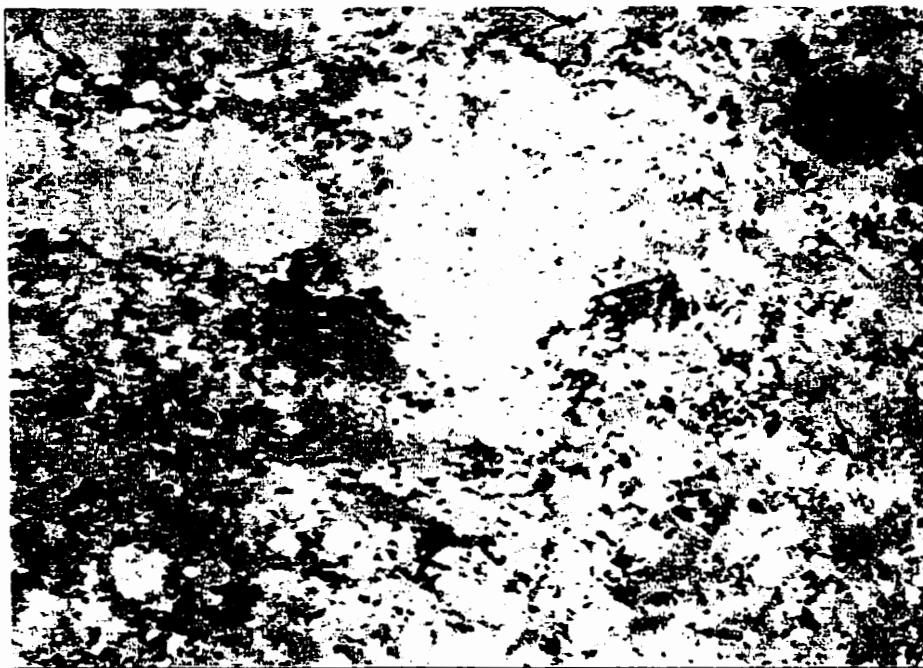


Figure 4.21: Disseminated fine-grained pyrite showing a concentration in a micritic core of an ooid. Sample JDH-8-4, PTS, RL, FOV = 0.85 millimetre.

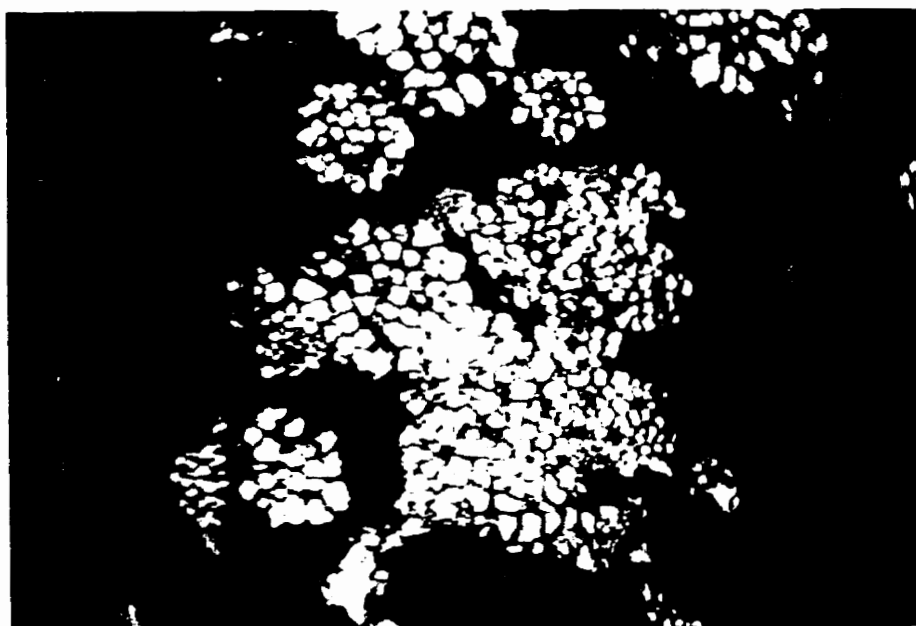


Figure 4.22: Cluster of fine-grained pyrite showing framboidal texture. Sample JPS 3, PTS, RL, FOV = 0.15 millimetre.

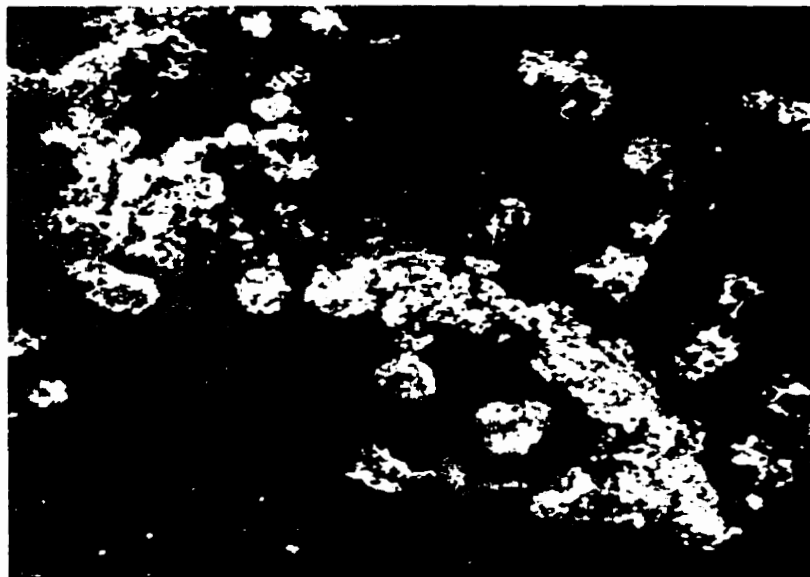


Figure 4.23: Oolite showing preserved clusters of fine-grained pyrite between concentric cortice layers. Sample 80,PTS, RL, FOV = 0.34 millimetre.

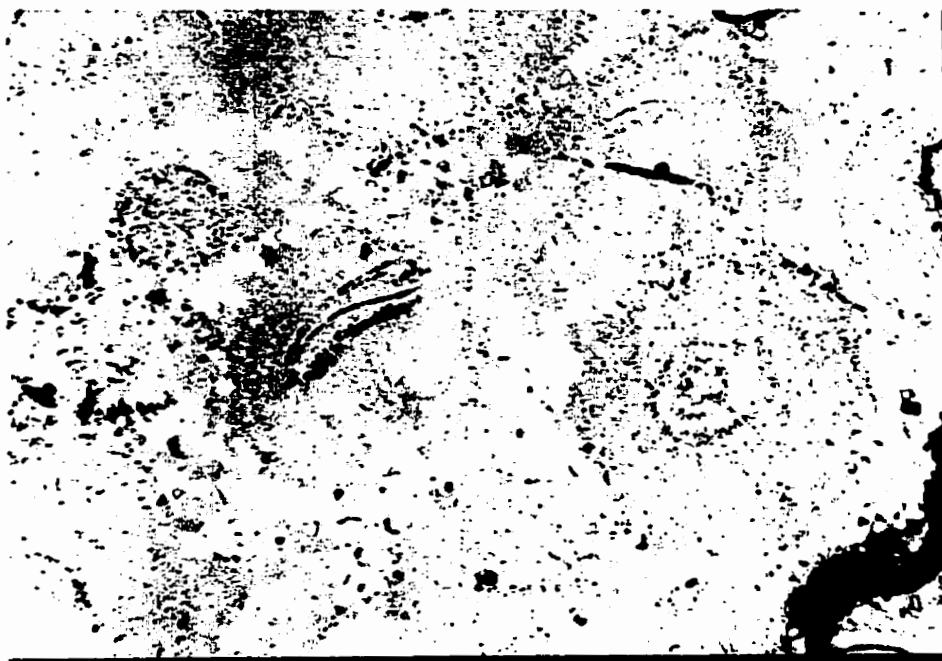


Figure 4.24: Micritized grainstone showing aggregates of fine-grained pyrite marking the contours of ghost ooids and coinciding with the preserved micritic envelopes. Sample 80,PTS,RL, FOV = 1.7 millimetres.

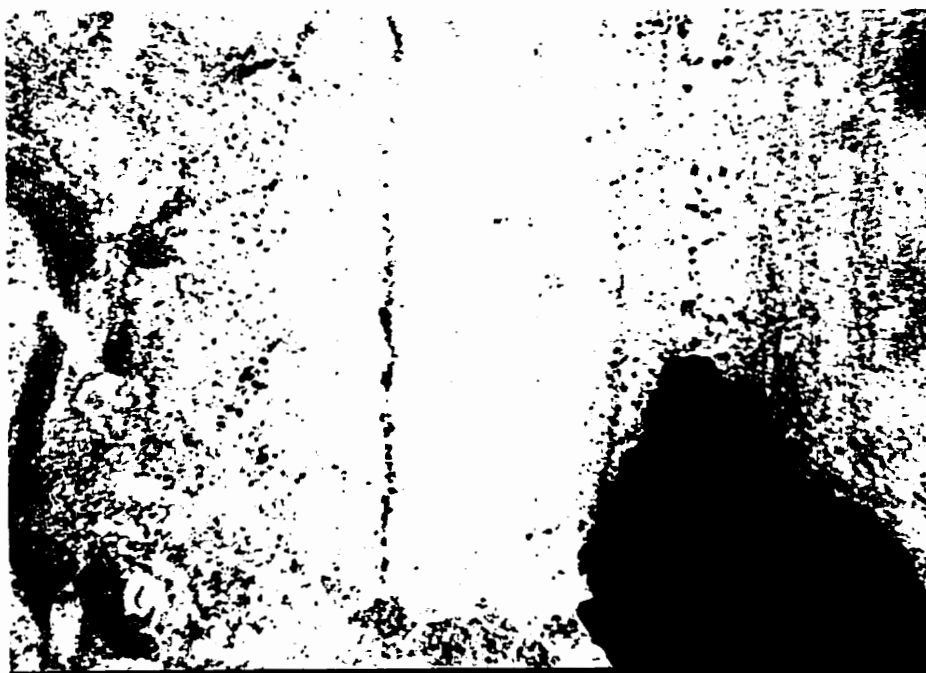


Figure 4.25: Dolomitic stromatolitic boundstone (light blue), showing fine-grained pyrite arranged along microlaminations (P) interpreted as former algal colonies with fenestral porosity. Note the presence of a large pyrite aggregate. Sample 75, PTS, PPL, FOV = 2.15 millimetres.

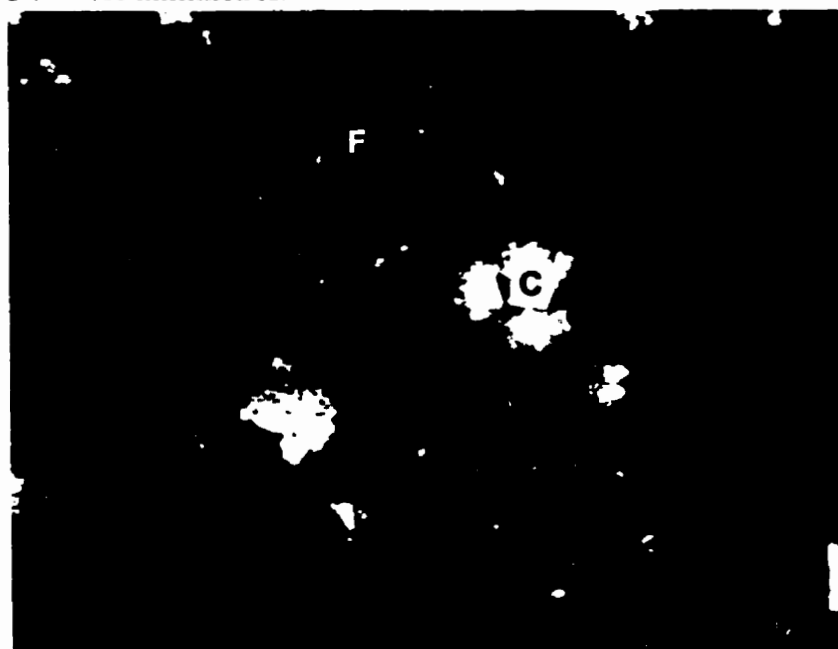


Figure 4.26: Coarse-grained pyrite (C) contrasts in size with fine-grained pyrite (F) (see within a micritic allochem, upper left). Note the euhedral coarse-grained pyrite which has formed from fine-grained pyrite, suggesting recrystallization of fine-grained pyrite. Sample 80, PTS, RL, FOV = 0.34 millimetre.

possible to see pyrite in bioturbations, where pelloids are an important source of organic matter. Pyritic nodular aggregates also form in interparticular spaces and are up to 1 or 2 centimetres in size (Fig. 4.10).

Coarse-grained euhedral pyrite, the second textural type, is typically larger than the very fine-grained pyrite described above: grains commonly measure 25 to 40 micrometres in size. This pyrite is as common as the very fine-grained type. It commonly occupies intergranular spaces rather than being present in allochems, in matrices or in cements. In some cases, aggregates of very fine-grained pyrite are partially redistributed and annealed locally to form coarse-grained euhedral pyrite (Fig. 4.26).

Neither type of pyrite has been identified in association with any non-primary sedimentary structure. Very fine-grained pyrite is interpreted to be an early diagenetic mineral, as suggested by its occurrence inside ooids and oncoids and by its association with micritization. Coarse-grained pyrite is interpreted to be a paragenetically later occurrence, probably formed in large part by recrystallization of the very fine-grained variety during sediment compaction and/or during basin deformation.

## 4.5 Gypsum

This mineral is the only sulphate observed by the author in the Yacoraite Formation, although barite and anhydrite are described by Espisúa et al. (1983). Several textural types of gypsum are present: idiomorphic crystals (gypsum laths), veinlets filled by polycrystalline aggregates, gypsum nodules and poikiloblastic cement.

Base-metal sulphide pseudomorphs after idiomorphic gypsum laths are present in some dolomitized oolitic grainstones of the Lower Yacoraite (Fig 4.27). These pseudomorphs

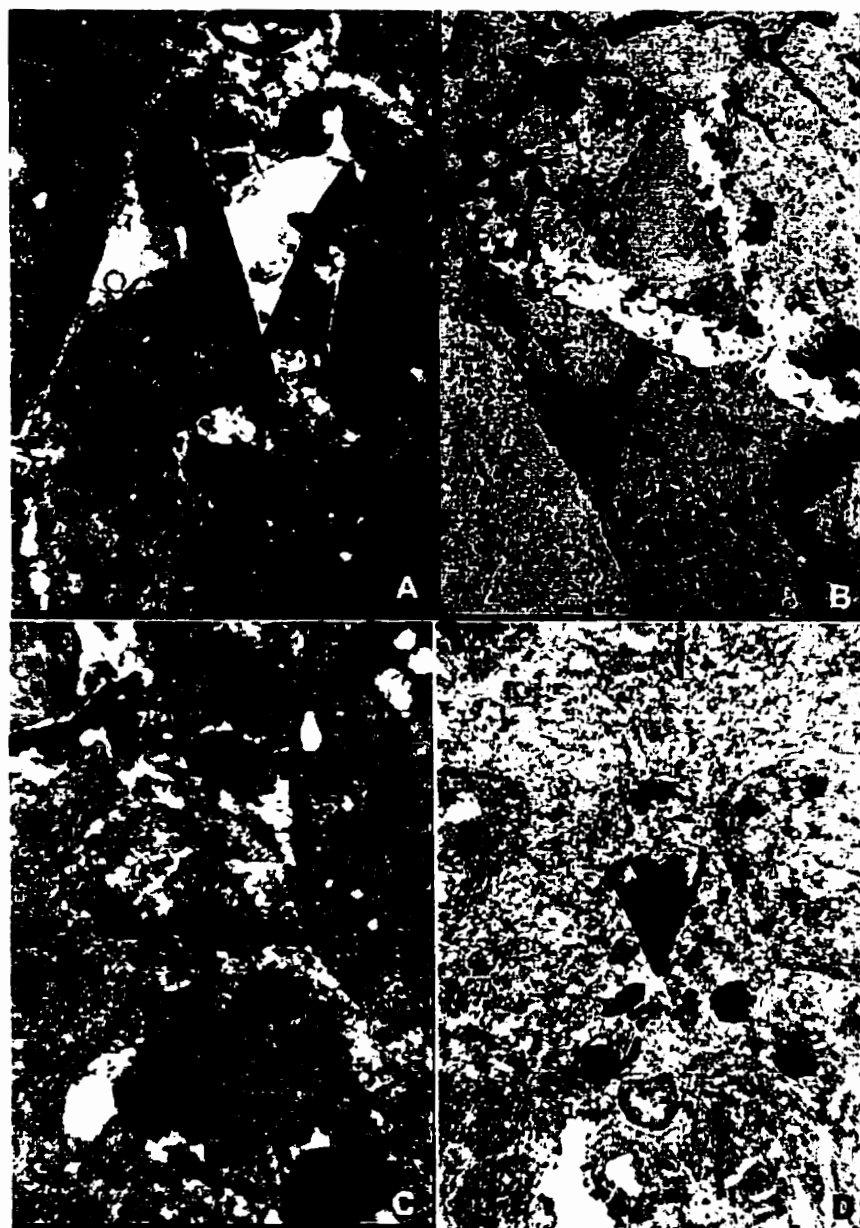


Figure 4.27: Pseudomorphic laths after gypsum. **A**, dolomitized grainstone showing sulfide pseudomorphs after gypsum laths. Gypsum is interpreted as being a very early cement deposited in interparticular spaces. Pyrite probably formed by early reduction of sulphate by anaerobic bacterial activity. Sample 20, PTS, PPL, FOV = 2.15 millimetres. **B**, detail of the same sulphide grain as in figure A, identified as chalcopyrite. RL, FOV = 1.7 millimetres. **C**, sulphide pseudomorph after a gypsum lath showing penetration into an ooid, suggesting that replacement by a more competent material predated packing visible elsewhere in the sample. Sample 21, PTS, PPL, FOV = 2.15 millimetres. **D**, sulphide lath after gypsum, not deformed, showing the 100 plane; in a packed and dolomitized grainstone. Sample also show preserved secondary porosity. Sample 22, PTS, PPL, FOV = 2.15 millimetres.

represent preserved, isolated, very early diagenetic, idiomorphic gypsum crystals, about 1 to 2 millimetres in length, formed in open spaces around ooids before the complete healing of the pores by carbonate cement. The gypsum laths, so formed and replaced by the more competent base-metal sulphides, were not readily deformed or broken during subsequent diagenetic compaction, indicating a relatively early emplacement of the sulphides.

Polycrystalline veins and veinlets containing gypsum are common in the Yacoraite Formation (Fig. 4.28). They are formed of subidiomorphic aggregates of gypsum crystals averaging about 20 micrometres in length, and oriented perpendicular to the walls of fractures. Such fractures cut through primary sedimentary structures, indicating that this gypsum post-dates both diagenesis and deformation.

Nodules of gypsum, formed of subidiomorphic crystals about 0.5 to 0.8 millimetres in diameter and disposed in radial form, are present mainly in the Upper Yacoraite siltstones (Fig. 4.29). The displacement of bedding during their growth indicates formation within an unlithified sediment and therefore during early diagenesis.

Finally, gypsum is also seen as a cement consisting of aggregates of subidiomorphic to idiomorphic crystals of variable size (averaging 0.4 millimetres in length) and growing in dissolution cavities (Fig. 4.30). This occurrence is constrained to the subaerially exposed calcareous rock types of Cerro del Plomo and Cerro del Cobre. It is not observed deeper than the present supergene alteration zone and, because of its occurrence in pores created by dissolution during recent exposure, this gypsum is interpreted to post-date all previous events including sedimentation, diagenesis, deformation, and presumably ore deposition.

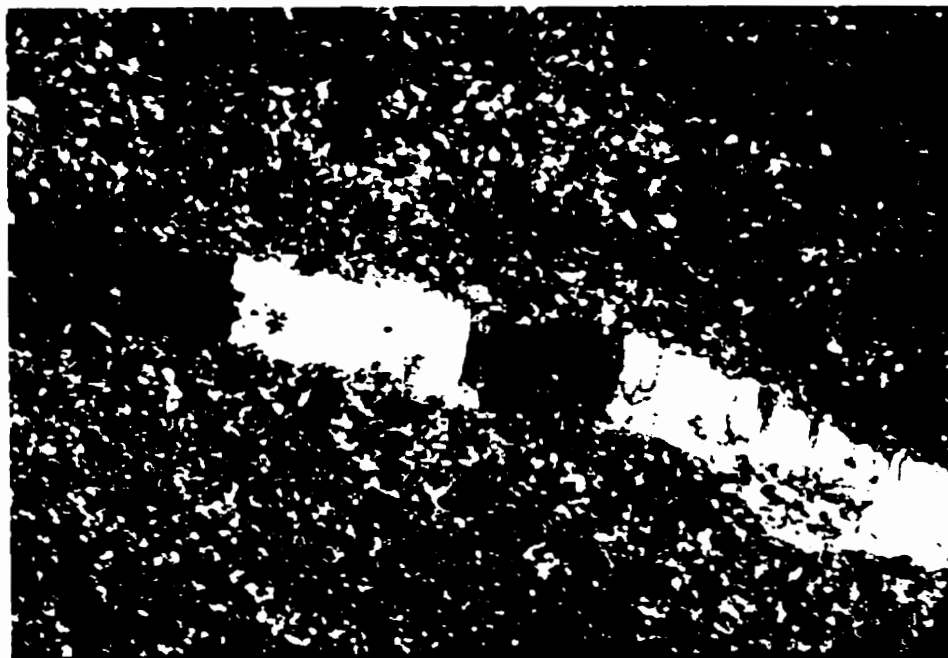


Figure 4.28: Gypsum filling a fracture in a silicified siltstone. Sample JDH-8-12, PTS, PPL, FOV = 2.15 millimetres.

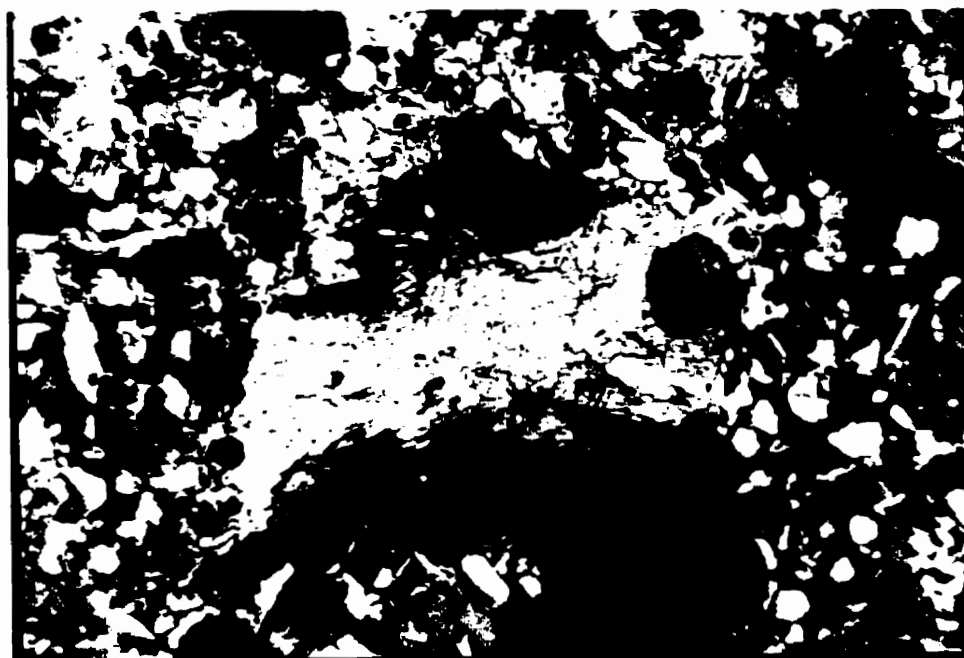


Figure 4.29: Displacive nodule of gypsum in a calcareous siltstone from the upper Yacoraite. Sample 68, PTS, XPL, FOV = 2.15 millimetres.

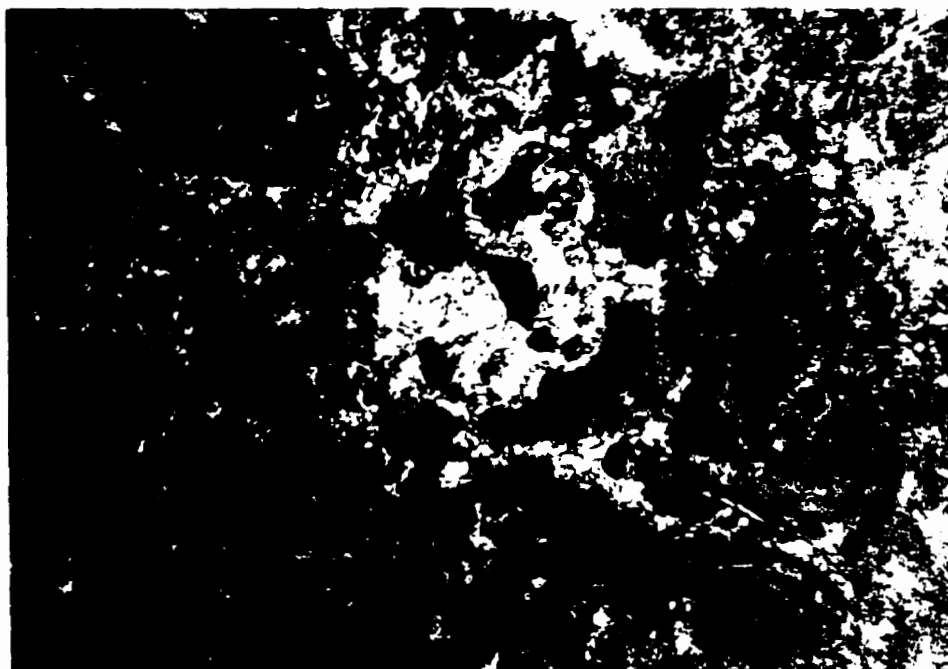


Figure 4.30: Poikiloblastic gypsum cement occluding secondary porosity created by dissolution. Sample JDH-8-4, PTS, XPL, FOV = 2.15 millimetres.

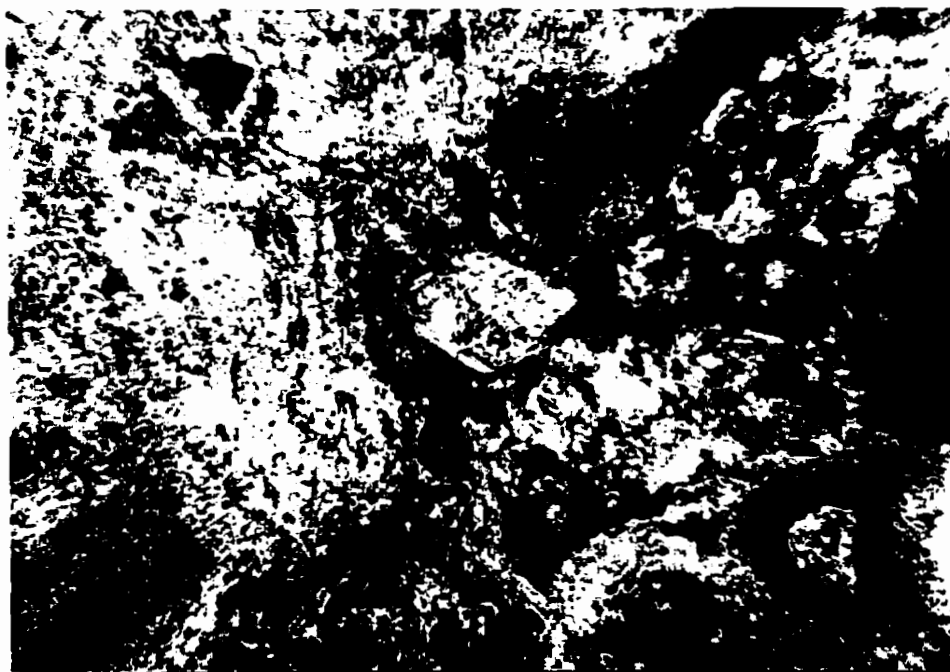


Figure 4.31: Authigenic feldspar showing inclusions of calcite. Sample 21, PTS, XPL, FOV = 0.85 millimetres.

## **4.6 Feldspars**

These minerals were observed as detrital grains and authigenic overgrowths. Detrital grains consist of potassium feldspar and, more rarely, microcline and plagioclase. Grains are subangular to subrounded, and the average size is medium sand. Alteration (weathering) of grains is not seen. Authigenic feldspar is observed as overgrowths on detrital grains (Fig. 4.31).

## **4.7 Phosphate**

Collophane is seen only in remnants of various aquatic life-forms such as fish or in detrital bone fragments ranging up to 1 millimetre in size (Fig. 4.32). Some fragments have pyritic fringes where organic matter produced reducing conditions suitable for anaerobic bacterial activity. The fragments are isotropic under cross-polarized transmitted light.

## **4.8 Hydrocarbons**

Vestiges of hydrocarbons are observed in the intergranular porosity of certain rock types, such as grainstones and packstones, in which case the hydrocarbons are most abundant in the most permeable fraction of the sediment. More commonly, hydrocarbons are associated with fractures that crosscut stratigraphy, including allochems, cements and matrix material (Figs. 4.33 and 4.34). The hydrocarbons remain soft and resemble tars. They occur in and nearly fractures and therefore the introduction of hydrocarbons is interpreted to post-date these fractures which are related to late deformation.

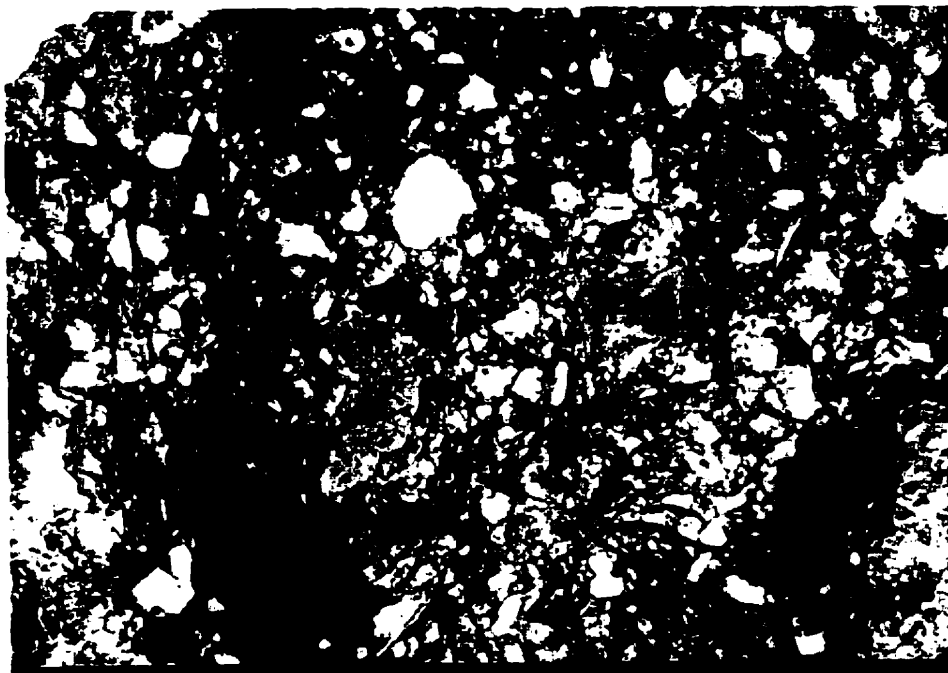


Figure 4.32: Phosphatic (P) remnants, interpreted to be collophane, in a greywacke with partially silicified matrix. Sample 6, PTS, PPL, FOV = 2.15 millimetres.

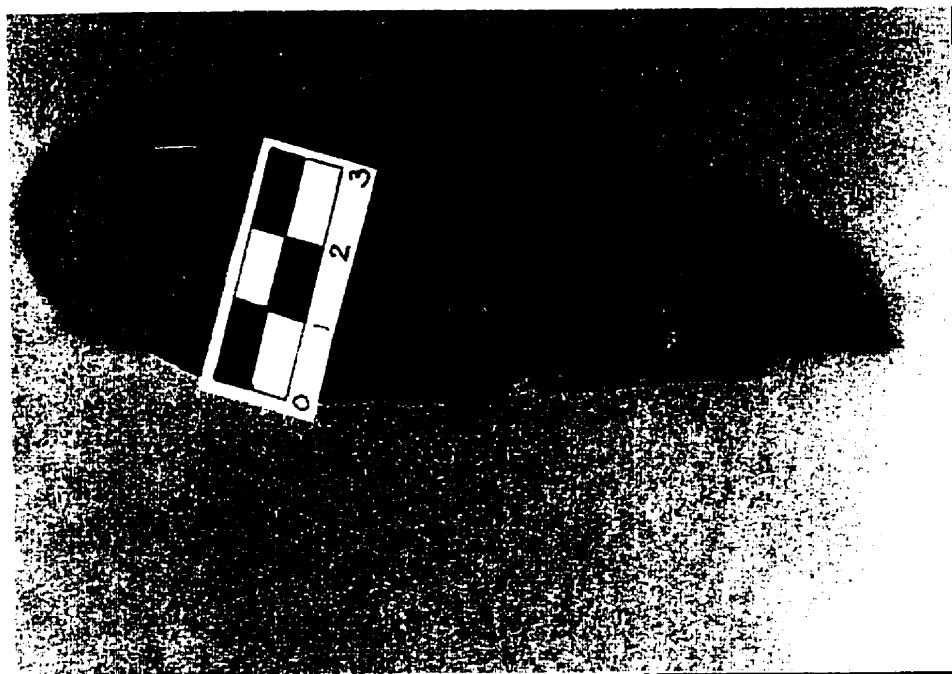


Figure 4.33: Fracture developed in a finely laminated siltstone showing a fracture that crosscuts stratification (visible on the side of the sample); the fracture is filled with hydrocarbon. Sample 6, CS. Scale is in centimetres.

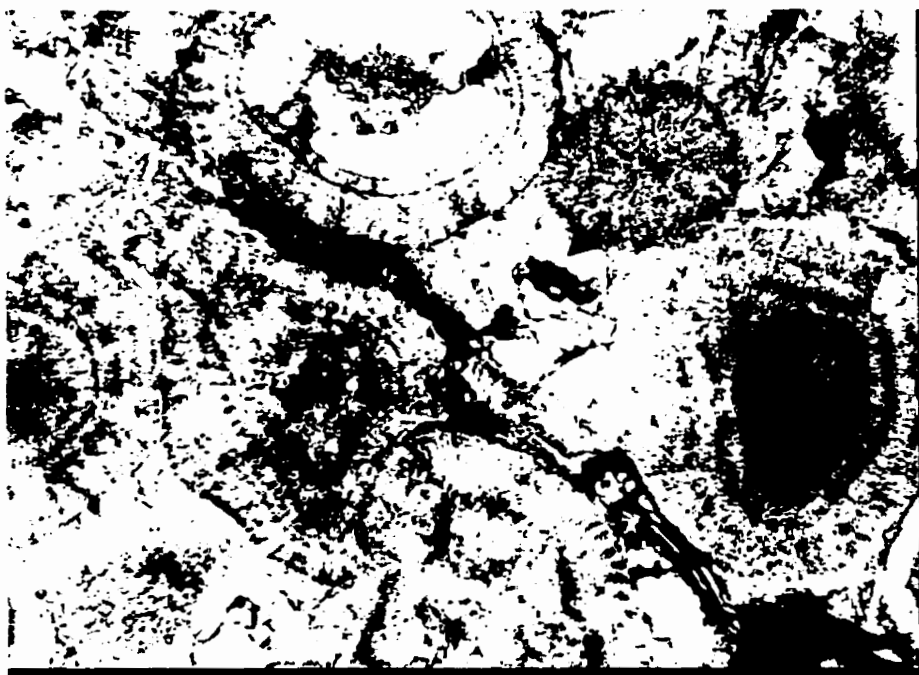


Figure 4.34: Hydrocarbon occupying a late fracture in a grainstone. Note that the fracture cuts through cement and allochems. Note the occurrence of hydrocarbons in the fracture and in the intracrystalline space (arrow), suggesting a late timing. Sample 79, PTS, PPL, FOV = 2.15 millimetres.

## **CHAPTER 5**

### **MINERAGRAPHY**

#### **5.1 Introduction**

Descriptions of the polished thin-section mineragraphy, zoning and paragenetic timing of both primary (hypogene) and then secondary (supergene) mineralization are given in this chapter. The thin-section petrography of the mineralized units, described in Chapter 4, is also referred to here in discussions of the sulphide mineralization. Pyrite, a pre-ore mineral already described in Chapter 4, is included here as part of the sulphide zoning only. Samples for this study are from drill cores and surface exposures (Figs. 5.19, 5.20, 5.21, 5.22 and Appendix 2).

#### **5.2 Primary Mineralization**

The dominant style of primary mineralization at Juramento consists of disseminated sulphides. Although seemingly randomly disseminated, the quantity and distribution of sulphide grains varies greatly across the lithostratigraphic units and apparently in direct proportion to the primary porosity of the host-rock; grainstones and packstones are clearly more highly mineralized in most cases than siltstones and mudstones. An exception to this last statement is the presence of mineralization in burrows in mudstones, a case where again the primary porosity is locally high.

All of the following descriptions result from petrographic and mineragraphic studies under both transmitted and reflected light. Textural observations under reflected light were used to determine the relation between sulphides and then to constrain the relative appearance of the various sulphides. The following primary sulphides have been identified: bornite, chalcocite, chalcopyrite, galena, sphalerite and tennantite-tetrahedrite. They are presented below in apparent order of deposition within the Yacoraite host-rocks (Fig. 5.1).

### 5.2.1 Sphalerite

Sphalerite is common in all drill holes as well as in many outcrops. It is most commonly present as irregular disseminated grains and sparse idiomorphic grains. The grain size is variable, ranging from approximately 100 micrometres in siltstones, to more than 2 millimetres in the intragranular and mouldic porosity of some grainstones. Under transmitted light, sphalerite may show growth bands. Also, sphalerite contains abundant fluid inclusions, generally less than 5 micrometers in size, as well as solid inclusions (dark material in transmitted light) that are presumed to be organic matter. In addition to its abundance as disseminated grains, sphalerite was observed in some microscopic-scale veinlets (typically 5 to 15 micrometres wide and 0.3 to 2 millimetres in length). Crushed grains of sphalerite were also observed in secondary stylolitic porosity (Fig. 4.7).

Sphalerite is consistently associated with pyrite and galena. Where associated with pyrite, it replaces the pyrite, forming rims on and in many cases occupying the spaces between euhedral fine-grained pyrite in pyritic aggregates (Fig. 5.2). Also, pseudomorphs were observed after very fine-grained euhedral pyrite. Where associated

|               | Syndiagenesis<br>(pre-ore) | Ore-Stage | Late Diagenesis<br>(post-ore) | Supergene<br>Alteration |
|---------------|----------------------------|-----------|-------------------------------|-------------------------|
| Pyrite        | ————                       |           |                               |                         |
| Sphalerite    |                            | ————      |                               |                         |
| Galena        |                            | ————      |                               |                         |
| Tennantite    |                            | ————      |                               |                         |
| -Tetrahedrite |                            |           |                               |                         |
| Chalcopyrite  |                            | ————      | ————                          |                         |
| Bornite       |                            | ————      |                               |                         |
| Chalcocite    |                            | ————      |                               |                         |
| Covellite     |                            |           |                               | ————                    |
| Digenite      |                            |           |                               | ————                    |
| Anglesite     |                            |           |                               | ————                    |
| Azurite       |                            |           |                               | ————                    |
| Malachite     |                            |           |                               | ————                    |
| Smithsonite   |                            |           |                               | ————                    |
| Cerussite     |                            |           |                               | ————                    |
| Fe-Oxides     |                            |           |                               | ————                    |
| Mn-Oxides     |                            |           |                               | ————                    |

Figure 5.1: Paragenetic sequence for the identified sulphide and alteration minerals from polished thin sections and polished sections of Juramento. See text for explanations.

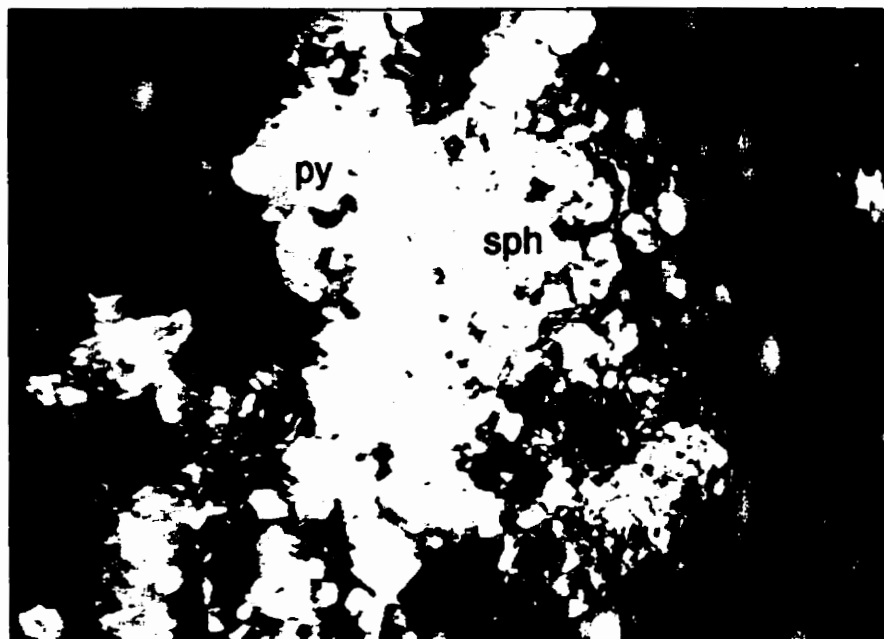


Figure 5.2: Sphalerite (sph), light grey, replacing an agglomeration of fine-grained pyrite (py). Sample JDH08-16, PTS, RL (oil immersion), FOV=0.12 millimetre.

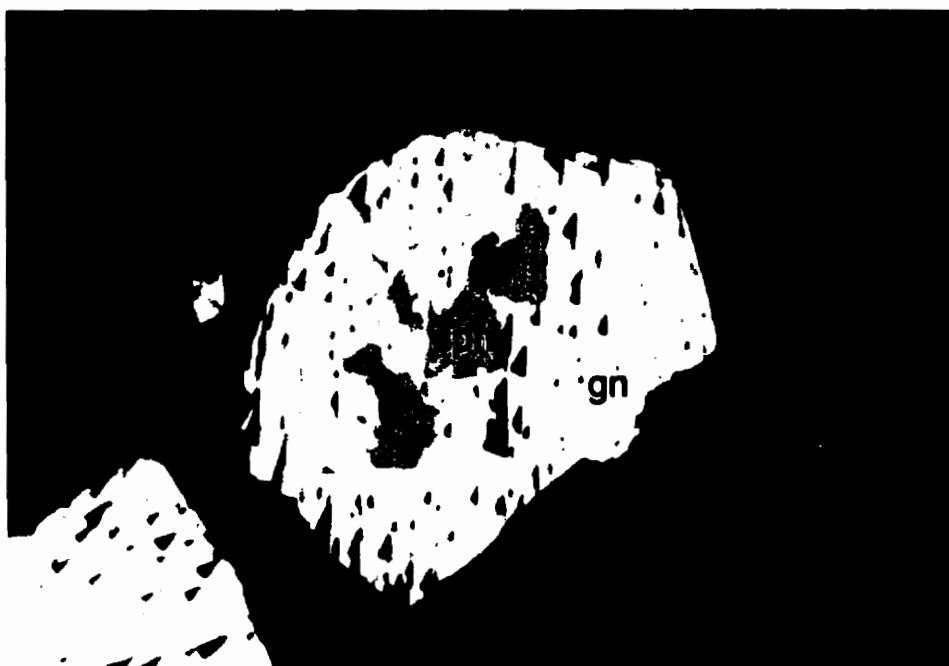


Figure 5.3: An assemblage of galena and sphalerite. Galena (gn) shows undisturbed cleavage and forms a rim around sphalerite (sph). Note the intergranular position of the assemblage. Sample 27, PTS, RL, FOV= 1.7 millimetres.

with galena, galena replaces sphalerite, commonly forming rims along the borders of sphalerite grains (Fig. 5.3).

Sphalerite is present throughout the Juramento stratigraphic section. In the lower to middle Yacoraite, it is observed as remnants within other sulphide assemblages such as chalcocite-bornite and chalcopyrite (Fig. 5.5). Sphalerite becomes more abundant than galena towards the middle-upper Yacoraite where it is the dominant sulphide together with pyrite. Towards the top of the Yacoraite Formation, the sphalerite abundance decreases with respect to pyrite, the dominant sulphide.

Sulphur isotopes values for sphalerite ( $n = 2$ ) clearly differ from those of pyrite; they are distinctly heavier, ranging from -25 to -8‰, compared with the range for pyrite of -43 to -28‰ (Fig. 5.4).

### 5.2.2 Galena

Galena forms isolated grains and also rims sphalerite and pyrite (Fig. 5.3). The grain size is highly variable, ranging from 40 micrometres to 1 or 2 millimetres in diameter. Galena invariably occupies the primary intergranular or secondary mouldic porosity as well as burrows. Galena is generally more abundant toward the top of the middle Yacoraite and rarely down to the base of the upper Yacoraite, although it is seen as inclusions in bornite, chalcopyrite and chalcopyrite-tennantite/tetrahedrite through the lower sections of the Yacoraite (Fig. 5.6). Espisúa and Amengual (1983) report negligible silver in this sulphide.

Some galena grains show deformed cleavages, suggesting their emplacement before

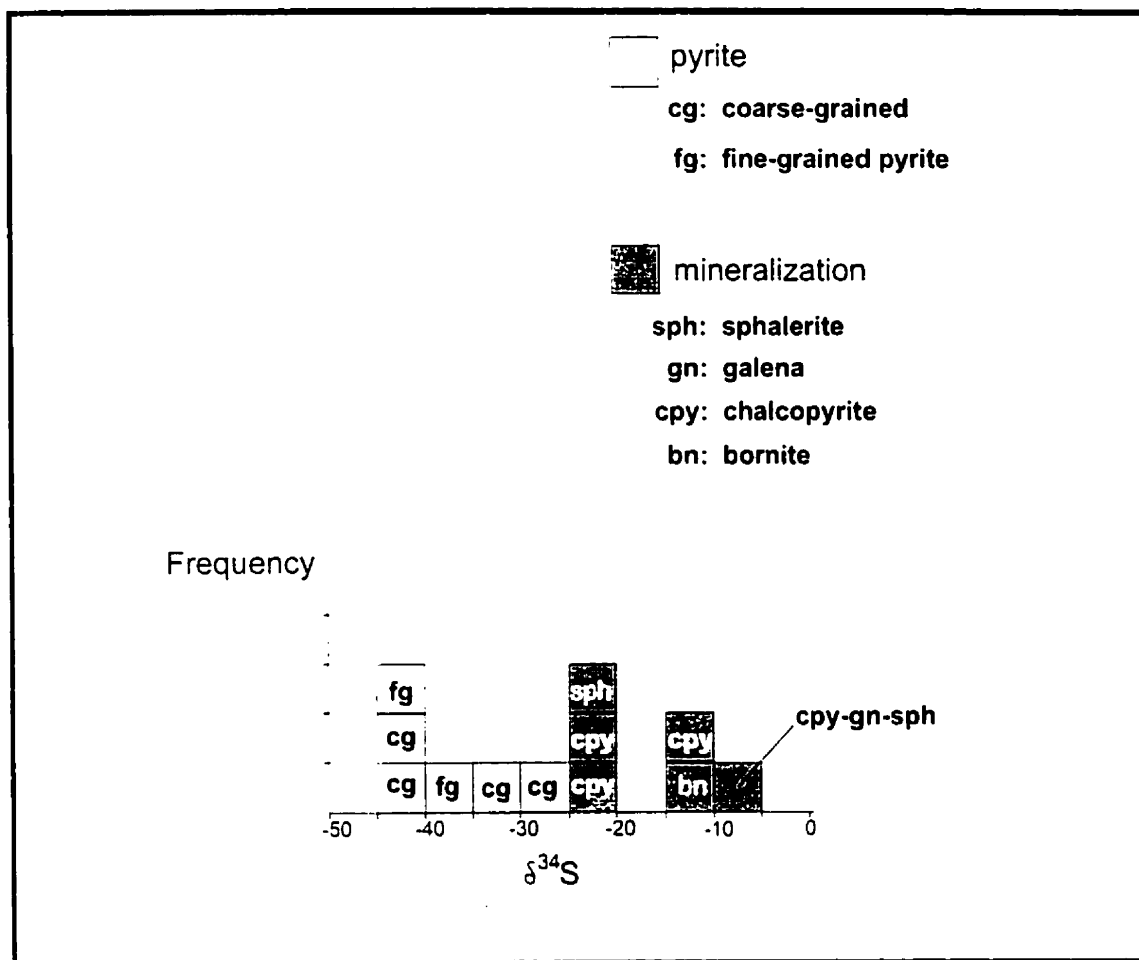


Figure 5.4: Sulfur isotope data from selected samples from Juramento. See text for explanations.

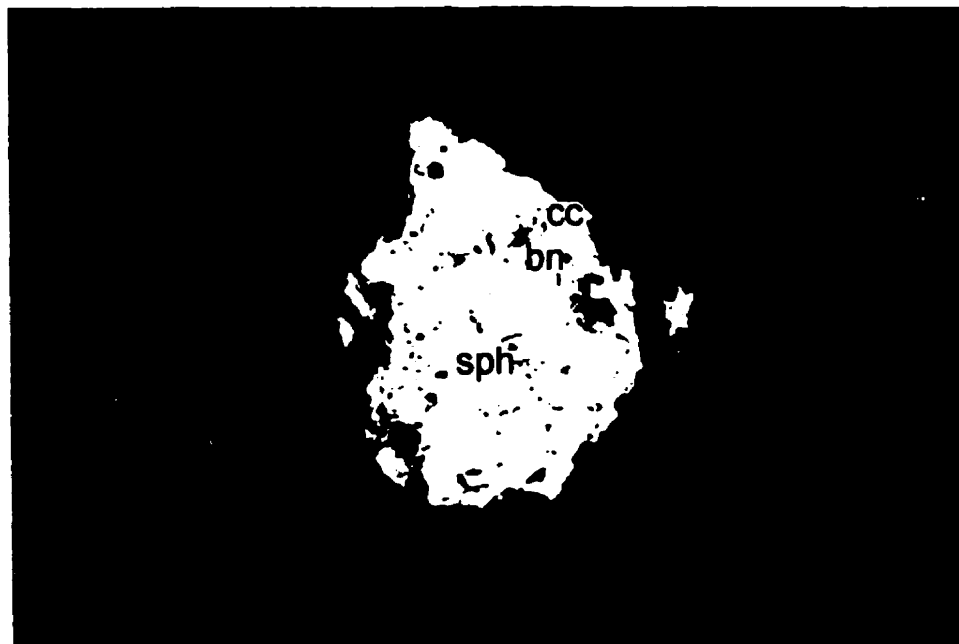


Figure 5.5: Assemblage of chalcocite (cc), bornite (bn) and sphalerite (sph). Sphalerite is replaced by bornite and both are replaced by chalcocite. Note the presence of chalcopyrite (yellow) in the crystalline structure of bornite only; this texture is interpreted as an exsolution. Sample 55, PTS, RL, FOV= 1 millimetre.

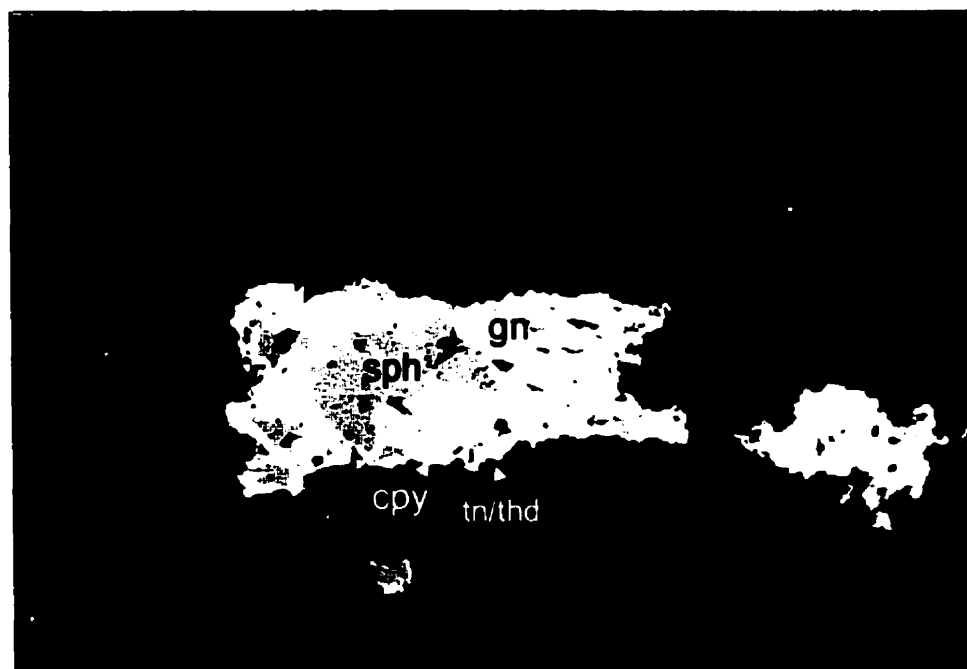


Figure 5.6: Galena and sphalerite grain replaced by a tennantite/tetrahedrite (tn/thd) - chalcopyrite (cpy) assemblage along edges. The texture is interpreted as sphalerite and galena preceding the cupriferous minerals. Sample 56, PTS, RL, FOV= 1 millimetre.

strong compaction or tectonic deformation of the sediments (Fig. 5.7). Galena is also observed in association with sphalerite in veinlets, as described for sphalerite above.

The sulphur isotopic analysis of a galena-sphalerite-chalcopyrite ( $n = 1$ ) assemblage gave a value of approximately  $-8\text{‰}$ , clearly heavier than pyrite, as is the tendency for the sulphur isotopic composition of most ore-stage minerals (Fig. 5.1).

### 5.2.3 Tennantite-Tetrahedrite

This sulphosalt is the only silver-bearing mineral detected during the study of polished thin sections. The composition has been determined by Espisúa et al. (1983) using X-ray diffraction and microprobe analyses. These authors state that the tetrahedrite component is greater than tennantite. Tennantite-tetrahedrite is not obvious in hand samples, but was readily detected in polished thin sections where it is typically associated with chalcopyrite and commonly forms narrow rims around galena and sphalerite (Figs. 5.6 and 5.8). Tennantite-tetrahedrite was also observed as inclusions and as penetrating veinlets in deformed galena and sphalerite in veinlets from outcrop samples from Cerro del Plomo. In detail, the rims of tennantite/tetrahedrite-chalcopyrite on galena-sphalerite assemblages are composed of aggregates of small idiomorphic to subidiomorphic grains, 10 to 30 micrometres in size. The presence of tennantite-tetrahedrite clearly depends on that of chalcopyrite; on the other hand, it may be associated with galena but not invariably.

The distribution of tennantite-tetrahedrite is closely related to that of chalcopyrite and to



Figure 5.7: A galena grain with deformed cleavage. This observation suggest the mineralization prior to deformation or strong compaction. Sample JPS-4, PS, RL, FOV= 0.87 millimetre.

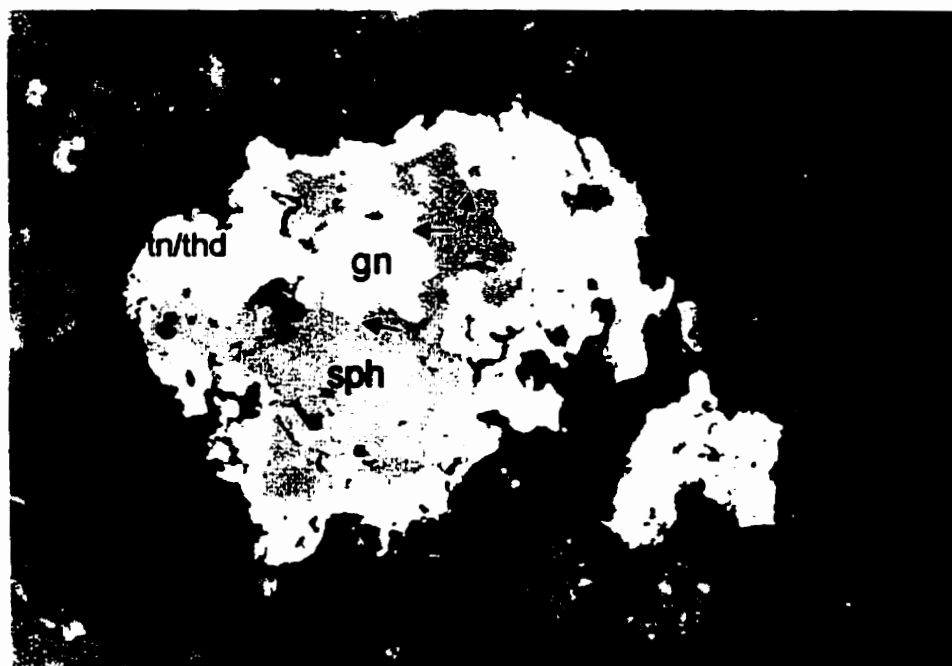


Figure 5.8: Tennantite/tetrahedrite (tn/thd) associated with chalcopyrite (yellow), replacing a grain composed of galena (gn) and sphalerite (sph). Note that chalcopyrite is located in the rims and in between the contact of galena and sphalerite (arrows). See text for explanation. Sample 63, PTS, RL, FOV=0.2 millimetre.

the primary intergranular porosity of the lower to middle Yacoraite; it may coexist with galena-sphalerite in the middle to upper Yacoraite.

#### 5.2.4 Chalcopyrite

This iron-rich cupriferous sulphide was observed as single isolated xenomorphic grains and aggregates of such grains, as well as pseudomorphs after both gypsum laths and very fine-grained euhedral pyrite. It also forms rims around paragenetically earlier sulphides (especially sphalerite and galena). The size of individual chalcopyrite grains varies, from 10 to 200 micrometres in size.

It occurs as pseudomorphs after gypsum laths in dolomitized oolitic grainstones (Figs. 4.27 and 5.9). The pseudomorphs vary up to 1 to 2 millimetres in length and are located in the primary intergranular porosity of the grainstone where the gypsum cement had sealed the pores, with a late dolomicritic cement. The pseudomorphs are only weakly deformed compared to the obviously strong packing of allochems (flattened ooids and spalled cortices) seen in the same polished thin-sections.

Chalcopyrite rims and includes pyrite, sphalerite and galena, and where found in contact with other cupriferous sulphides such as bornite and chalcocite, it is rimmed by these paragenetically later ore-stage sulphides (Fig. 5.10 and 5.11). Chalcopyrite commonly forms rims around sphalerite and galena and is intergrown with tennantite-tetrahedrite (Fig. 5.8).

One unusual texture repeatedly seen consists of a narrow band of chalcopyrite between a rim of galena partially replacing sphalerite; generally chalcopyrite replaces galena but in

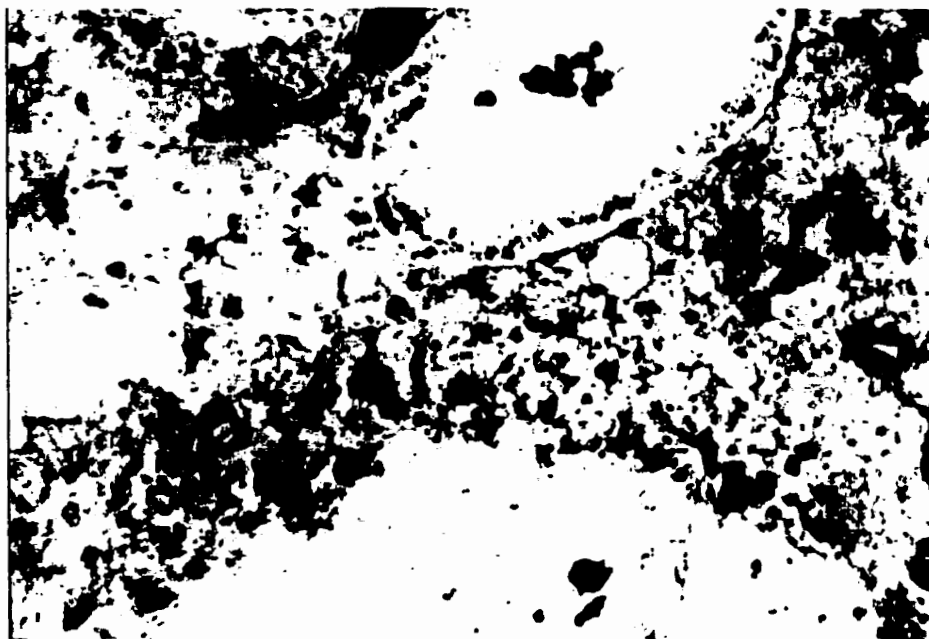


Figure 5.9: Chalcopyrite pseudomorph after gypsum laths in an oolitic grainstone. Note that the lath penetrates an ooid suggesting replacement before compaction. Sample 20, PTS, RL, FOV= 1.7 millimetres.

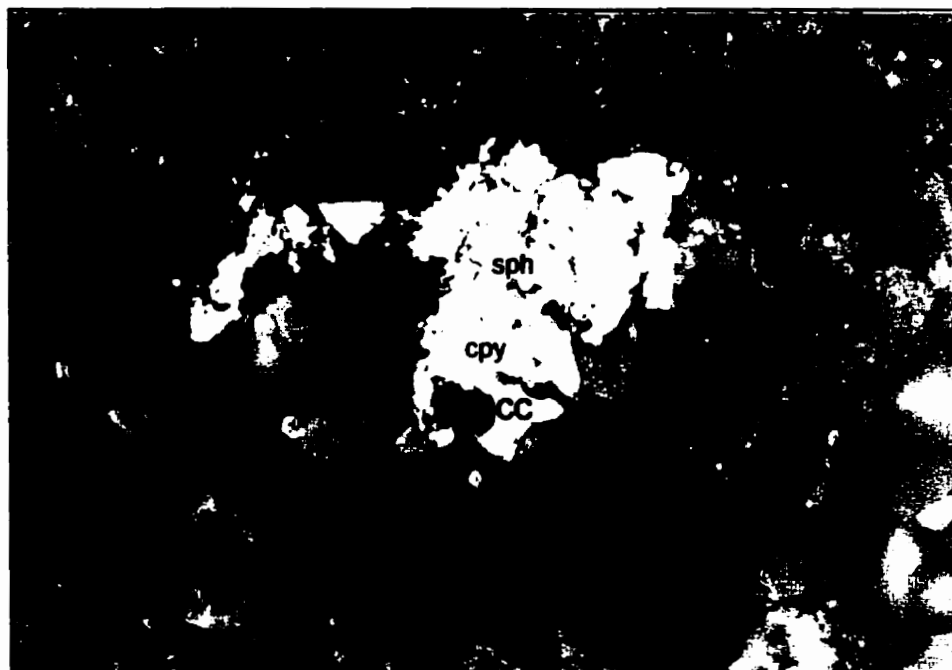


Figure 5.10: Chalcopyrite (cpy) replacing sphalerite (sph) and both replaced by chalcocite (cc). Sample 60, PTS, RL, FOV=0.2 millimetre.



Figure 5.11: Chalcopyrite (cpy) grain replaced by bornite(bn) and later by chalcocite (cc). This texture suggests that chalcopyrite is earlier than bornite and that chalcocite is the latest mineral. Sample 58, PTS, RL, FOV=0.2 millimetre.

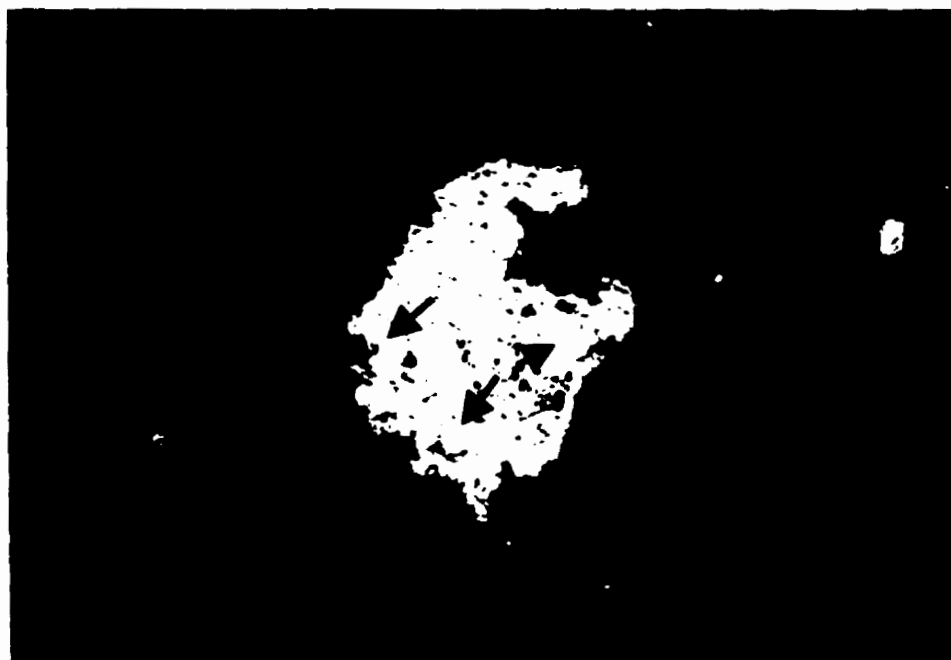


Figure 5.12: Replacement of a galena-sphalerite grain by chalcopyrite (arrow). Note the location of the chalcopyrite in the boundary between galena and sphalerite. Sample 56, PTS, RL, FOV= 1 millimetre.

this case the chalcopyrite appears to occur spatially and paragenetically between early sphalerite and later galena (Fig. 5.12). However, on closer inspection, the same chalcopyrite clearly rims and veins galena in many cases, and therefore the apparent rim of galena over chalcopyrite is actually a case where chalcopyrite preferentially seeks to replace remnant cores of sphalerite rather than the rims of galena. In effect, the sphalerite represents a more unstable sulphide than galena in the presence of a cupriferous solution, and at the microscopic scale, the chalcopyrite represents solid-state diffusion across galena to reach the core of sphalerite (or the chalcopyrite reached the core sphalerite via minor veinlets not seen in the two-dimensional plane of the polished section).

Also, chalcopyrite was observed in stylolites which follow along bedding planes and in a few case the stylolites abruptly crosscut stratigraphy; these stylolites were mistaken for veinlets in earlier reports, giving the false impression that a structural control of copper emplacement was important at Juramento.

As for the stratigraphic distribution of chalcopyrite, it was observed as traces within the chalcocite/bornite-dominant assemblage in the lower Yacoraite (see below), is a dominant phase in the middle Yacoraite, and is rare again in the transition into the pyritic upper Yacoraite.

Chalcopyrite-dominant samples ( $n = 3$ ; Fig. 5.1) show a sulphur isotope range from -25 to -12‰ and chalcopyrite-galena-sphalerite assemblage shows a value of -8‰. Note that chalcopyrite has approximately the same values as earlier ore sulphides and is consistently heavier isotopically than pyrite.

### 5.2.5 Bornite

Bornite was observed as irregular disseminated grains, as aggregates of fine grains and as pseudomorphs after very fine-grained euhedral pyrite. Individual grains within disseminated grains and aggregates of bornite vary in size from 10 to more than 800 micrometres in diameter. They occupy primary intergranular and secondary diagenetic porosities.

Two distinct varieties of bornite were found: a so-called "anomalous" or "pink" bornite commonly considered sulphur-rich, and a purple bornite commonly considered sulphur-poor and copper-rich (Ramdohr, 1969)(Figs. 5.13 and 5.14). Purple bornite is observed only in samples from the lower Yacoraite, whereas pink bornite is found to have a less restricted distribution extending over the lower and middle Yacoraite. Pink bornite is more abundant than the purple variety.

The most common bornite occurrence is a contact association with chalcocite (see below) in which chalcocite forms irregular rims around bornite (Figs. 5.13 and 5.15); in most cases, the bornite in contact with chalcocite is purple. Bornite also forms a boundary contact with paragenetically earlier sulphides such as sphalerite, galena and chalcopyrite. Inclusions of pyrite are common. Bornite is found from the lower Yacoraite up to the transition into the middle Yacoraite. As with chalcopyrite, bornite is found in stylolitic structures in some cases.

Pink bornite may include a basket-weave intergrowth of chalcopyrite lamellae (Fig. 5.16). This texture is generally interpreted as an exsolution of chalcopyrite resulting from excesses of sulphur and iron in the host bornite. Such "anomalous" bornite could be a metastable "redbed copper" formed initially during rapid crystallization at low temperatures (Yund and Kullerud, 1966). During subsequent mild annealing, as during

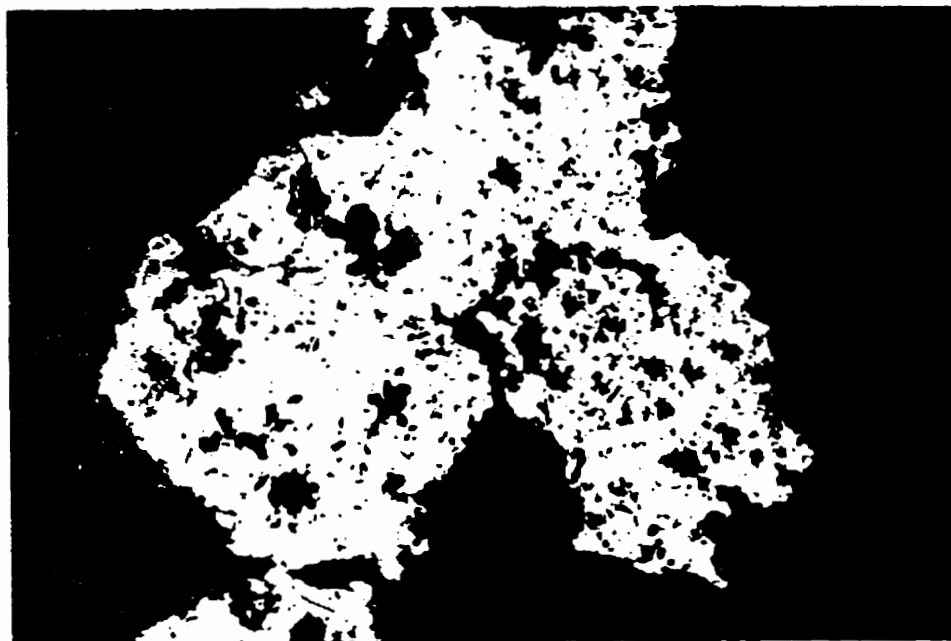


Figure 5.13: Purple bornite showing a narrow irregular replacement rim of chalcocite. Sample 31, PTS, RL, FOV= 1 millimetre.

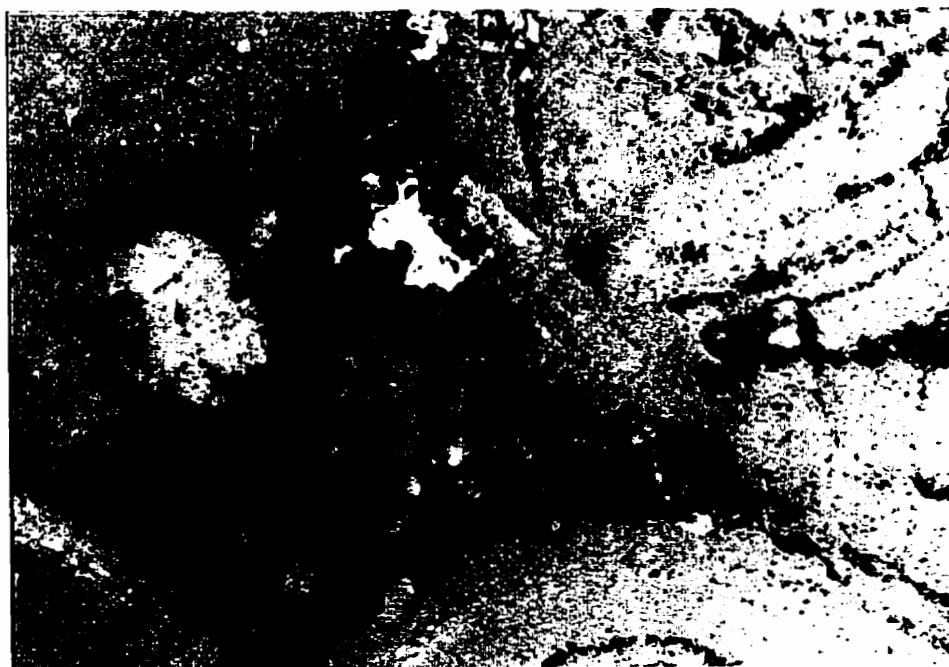


Figure 5.14: Pink bornite in interparticular porosity. Sample 57, PTS, RL, FOV= 1 millimetre.



Figure 5.15: Purple bornite replaced by chalcocite. Note the presence of some chalcopyrite with the bornite. Sample 92, PTS, RL, FOV= 1 millimetre.

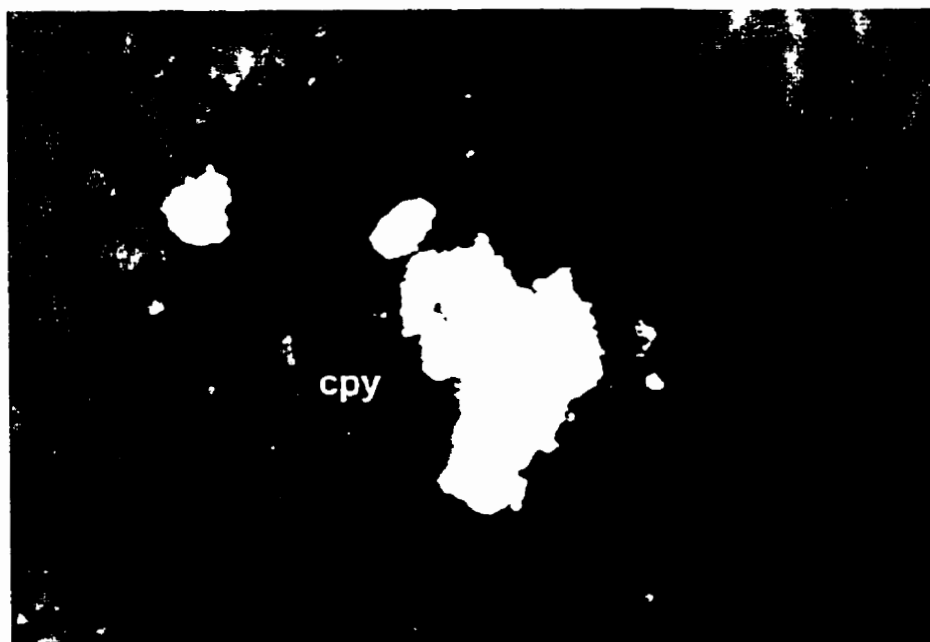


Figure 5.16: Pink bornite showing basket weave exsolution of chalcopyrite. See text for explanation. Sample 62, PTS, RL, FOV=0.2 millimetre.

host-rock burial, elements in excess may exsolve to form chalcopyrite along the crystallographic planes of bornite. Brown (1971) showed that a temperature of 75°C was sufficient to incite this exsolution from the pink bornite of the White Pine deposit.

The sulphur isotopic composition of bornite ( $n = 1$ ; Fig. 5.1) is approximately -10‰, again showing that bornite, as with other ore sulphides, is isotopically heavier than pyrite.

#### 5.2.6 Chalcocite

Chalcocite is a common disseminated copper-rich sulphide, although it is subordinate in abundance to bornite. Typically, individual chalcocite grains are irregular in shape and of variable size, ranging from 10 to more than 200 micrometres in diameter (Fig. 5.18). It is observed as rims around all earlier sulphides and is not seen as inclusions in other sulphides. The most common contact relationships are with bornite (generally the purple type) and chalcopyrite (Fig. 5.17)

Most of the chalcocite occupies primary intergranular porosity. Its occurrence is almost entirely restricted to the lower Yacoraite, although it has been found up to the transition into the middle Yacoraite.

### 5.2 Primary Sulphide Zoning

A metal zoning represented by primary sulphide minerals including pyrite is observed in drill core logging and analyses and in stratigraphic mapping across the Juramento area. For example, zoning is clearly shown in bore hole JDH-13 on Cerro del Plomo (Fig. 5.19) in which a section cross-cutting the stratigraphy presents a well-mineralized core

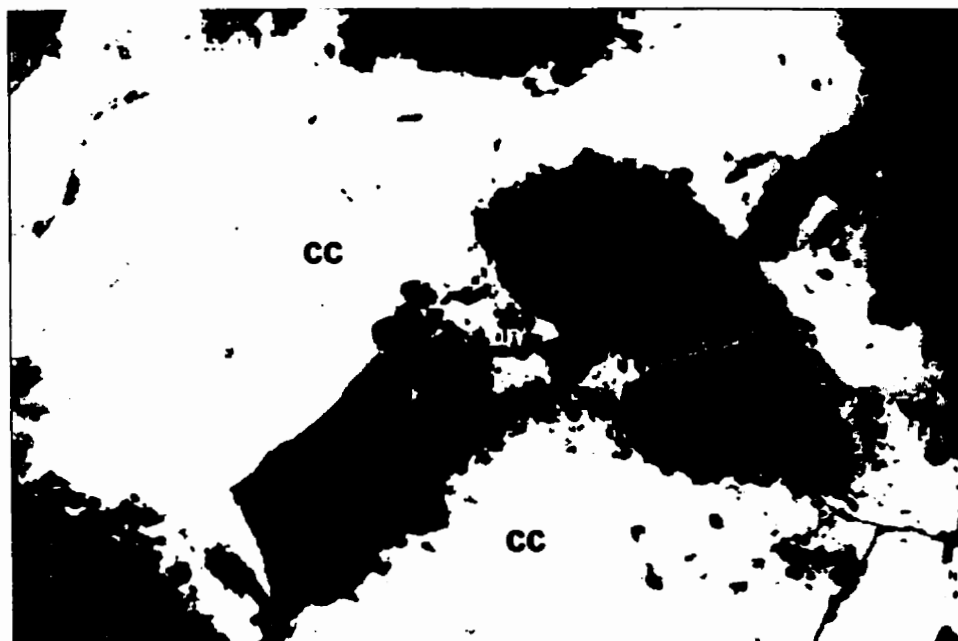


Figure 5.17: Chalcocite (cc) replacing bornite (bn) in interparticular space. Note the disseminated remnants of bornite in other areas. Sample 58, PTS, RL, FOV = 0.5 millimetre.

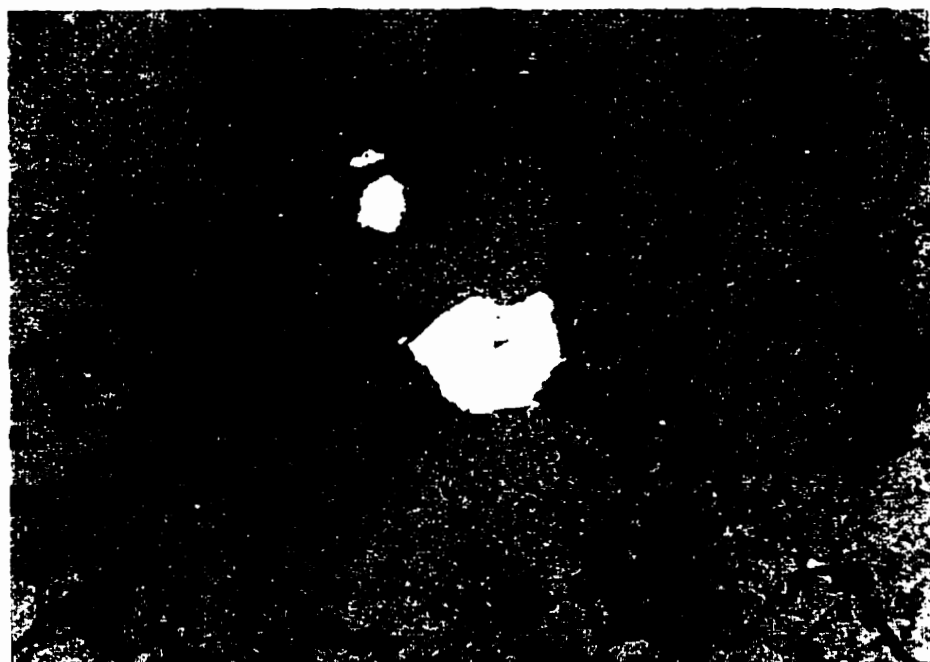


Figure 5.18: Disseminated chalcocite. Note a replacement within a deformed ooid. Sample 37, PTS, RL, FOV = 1.7 millimetres.

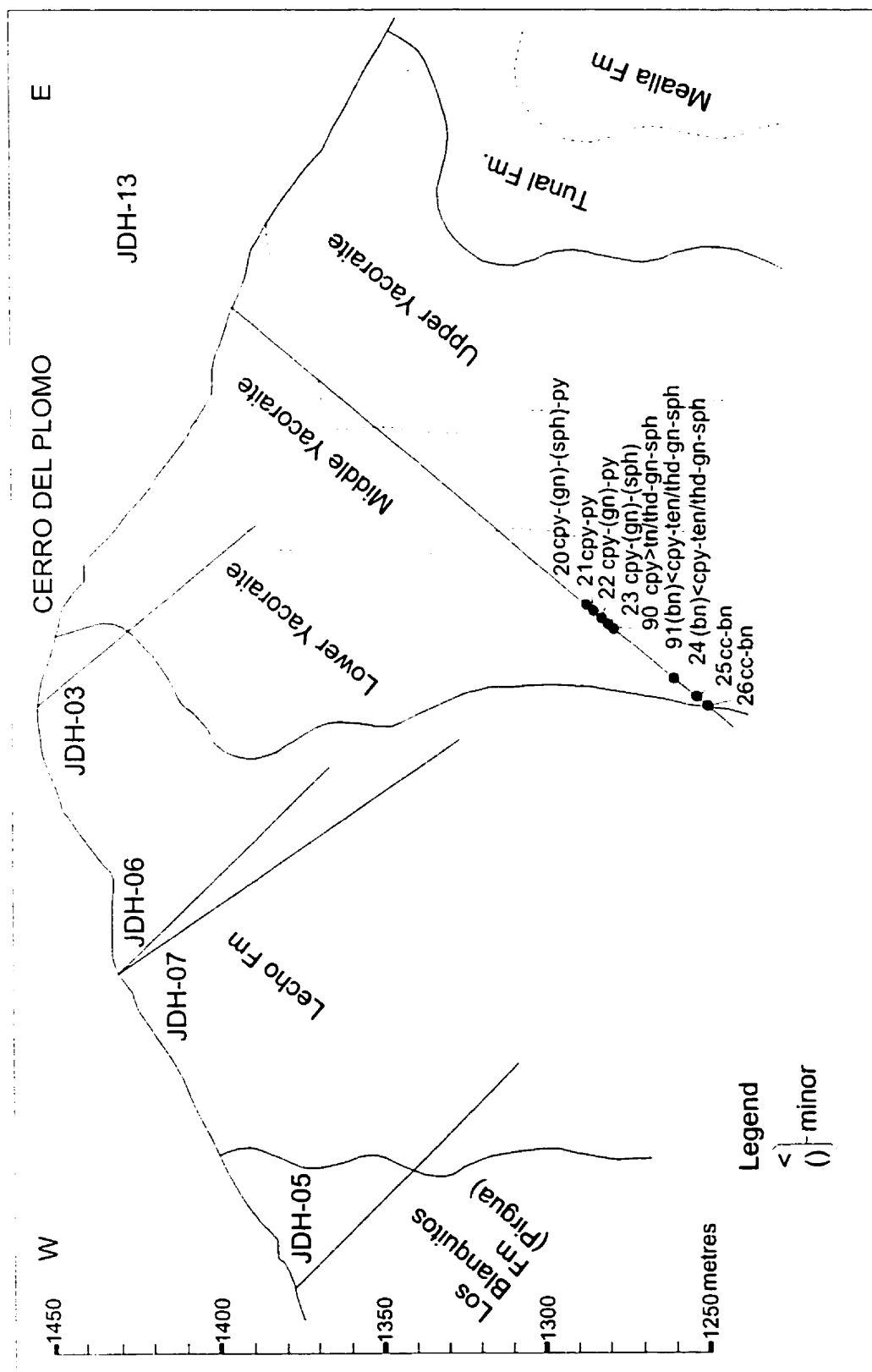


Figure 5.19: Schematic cross-section of 'the line a-a' across Cerro del Plomo (see Figure 2.7) with a projection of drill hole JDH-13 and showing the main lithologies and sulphide assemblages present in the samples from bore hole. Vertical scale equals horizontal scale. Geology modified from Rotzien and Wormald (1998).

section from the Lecho-Yacoraite transition to the upper Yacoraite and Tunal Formation. The zoning may be combined with the paragenetic sequence to visualize the overall zoning and its origin. Stratigraphically basal chalcocite rims and replaces bornite which is more abundant towards upper portions of the lower Yacoraite. At the latter stratigraphic level, chalcocite becomes negligible and chalcopyrite appears in trace amounts, with bornite replacing that chalcopyrite. A few metres higher, in the transition from lower to middle Yacoraite, bornite is absent and only chalcopyrite is observed: there, it replaces galena and sphalerite. Galena replaces sphalerite which continues upward replacing pyrite. In the upper Yacoraite, sphalerite decreases in abundance and pyrite is the dominant sulphide in the transition into the Tunal Formation. Copper-rich minerals have obviously advanced stratigraphically upward across earlier lead-rich and still earlier zinc-rich zones that replace pre-ore pyrite.

Drill hole JDH-25 on Cerro del Cobre (Fig. 5.20) also shows this general metal (and sulphide) zonation. The drill hole is the least complex section at Juramento in terms of its normal stratigraphic and structural profile. Furthermore, most of the Yacoraite section is well below the influence of supergene oxidation (seen here in the uppermost 20 to 30 metres where the greenish clays, siltstones and carbonates of the Tunal Formation and the reddish clays and sandstones of the Santa Barbara Subgroup, are observed). The drill hole crosscuts the lower, middle and upper Yacoraite Formation and the lower end of the hole penetrates a few metres into the Lecho Formation.

The abundance of copper in this drill hole is low compared to other drill holes. Nevertheless, the copper-rich sulphide chalcopyrite is observed in the lower portions of the core where it replaces galena and sphalerite. Upward from the transition between lower and middle Yacoraite, chalcopyrite decreases in abundance and becomes rare to absent, and galena and sphalerite are the most abundant sulphides. Higher in the strata, galena replaces sphalerite. From the transition between middle and upper Yacoraite to

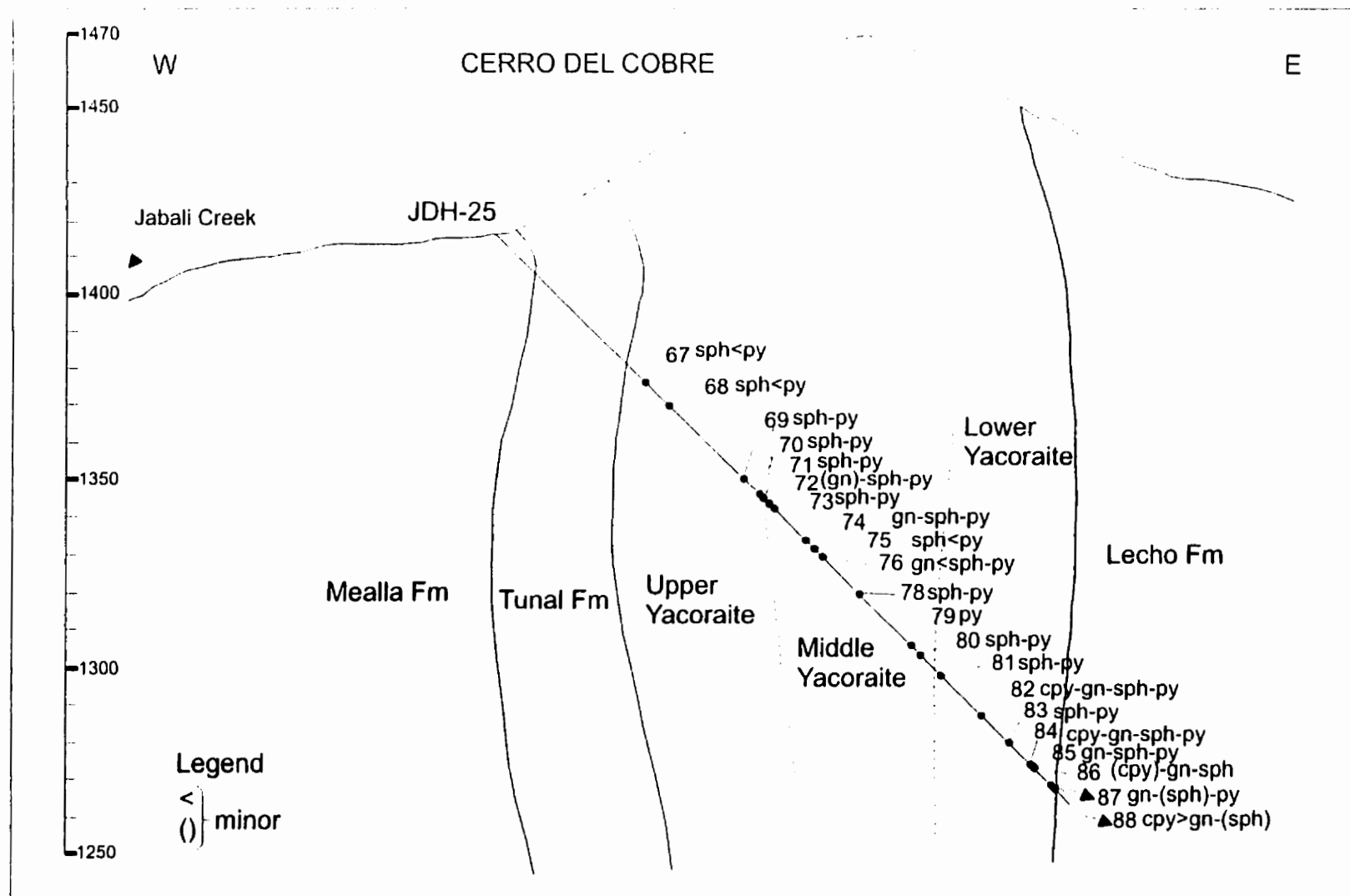


Figure 5.20: Schematic cross-section from line b-b' (see Figure 2.7), with drill hole JDH-25 used for the main stratigraphic control and attitude. Sulphide zoning is explained in the text. Geology modified from Rotzien and Wormald (1998).

the top of the Yacoraite section, sphalerite is more abundant than galena, and it is observed to replace and form pseudomorphs after very fine-grained pyrite. Towards the top of the Yacoraite Formation and into the greenish El Tunal Formation, the sulphide assemblage consists almost solely of pyrite. Tennantite-tetrahedrite are present in the transition between the chalcopyrite zone and the galena-sphalerite dominant zone.

Other drill holes to the south of JDH-25 on Cerro del Cobre (JDH-15, 16 and 19) confirm this sulphide zonation. The cupriferous sulphides are richer in copper, consisting of abundant chalcocite and bornite which show replacements of chalcopyrite and tennantite-tetrahedrite.

A remarkable zonation is seen in drill core JDH 19 (Cerro del Cobre) (Fig. 5.21) which crosscuts an apparent simple fold. From the collar down, the first metres of core intersect a tectonically complex zone, after which the core cuts what is interpreted to be middle Yacoraite and then a fold in the lower Yacoraite. Still deeper, the drill core leaves the hinge of a fold and passes into the middle Yacoraite again so that the lower to middle Yacoraite transition is repeated. In thin-section samples of this core, the most abundant sulphides in the middle Yacoraite are galena and sphalerite, with traces of chalcopyrite. Chalcopyrite replace galena, and galena consistently replaces sphalerite. In the lower Yacoraite, bornite and chalcocite are predominant over chalcopyrite, galena and sphalerite. Also, chalcocite and bornite invariably rim chalcopyrite, galena and sphalerite.

Surface samples from the Lecho Formation, and drill core samples from the transition between the Lecho and lower Yacoraite, host mineralization in some cases. If sulphides are present, they invariably consist of copper-rich sulphides such as chalcocite and bornite. Fine-grained pyrite associated with calcareous allochems such as lumps or ooids is present too (Figs. 3.3 and 3.4).

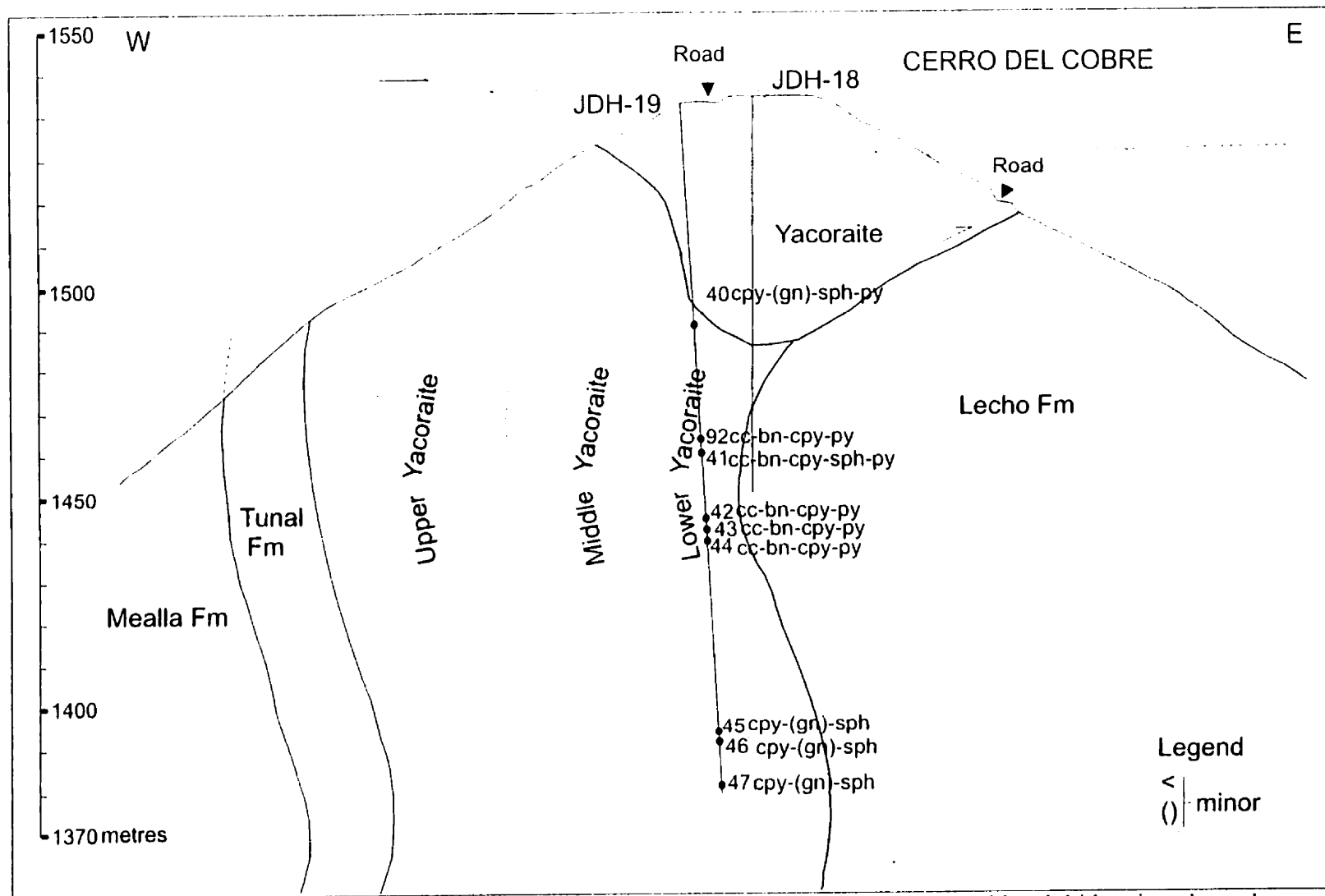


Figure 5.21: Schematic cross-section from line c-c' across Cerro del Cobre (see Figure 2.7) with sulphide mineralogy shown for drill hole JDH-19. Geology modified from Rotzien and Wormald (1998).

Lateral zoning along bedding may also be seen in the above descriptions, although structural complications commonly make stratigraphic reconstructions difficult. Nevertheless, in JDH-20 (Cerro del Cobre)(Fig. 5.22), the drill core apparently remains in the transition between the middle and lower Yacoraite for 70 metres of borehole. The sulphides show an apparent lateral zonation consisting of a galena-sphalerite dominant assemblage in the upper drill section, a chalcopyrite and then bornite-chalcopyrite zone in the middle drill section, and then a chalcocite-bornite dominant assemblage in the lower core section. Below those 70 metres, the borehole cuts the lower Yacoraite where chalcocite and bornite are the abundant sulphides.

Lateral zoning is also apparent between drill core across the Juramento property. For example, in JDH-13 on Cerro del Plomo, copper-rich minerals are abundant in the lower Yacoraite and lead- and zinc-rich minerals occur in the middle and upper Yacoraite, whereas in JDH-25 on Cerro del Cobre, only minor amounts of chalcopyrite are seen in the lowermost Yacoraite and lead- and zinc-rich sulphides occur in the overlying strata.

From these descriptions, a general metal/sulphide zoning can be seen (Fig. 2.8). A broad vertical and possible lateral zoning of sulphide species is observed relative to the stratigraphic column at Juramento. In the most cupriferous sections, copper-rich sulphides are generally concentrated in the lower Yacoraite and occasionally in the upper Lecho, although in some cases they are present up to the transition between the middle and upper Yacoraite, where they overlap the lead-dominant zone. The galena-dominant zone is mainly present in the middle Yacoraite and it also progressively overlaps the sphalerite-dominant zone towards the upper Yacoraite. Still further above, pyrite is the dominant sulphide toward the top of the upper Yacoraite.

Within the copper-sulphide zone, there is also a zonation with respect to the copper-rich and iron-bearing species. Copper-rich sulphides (chalcocite, bornite) tend to concentrate

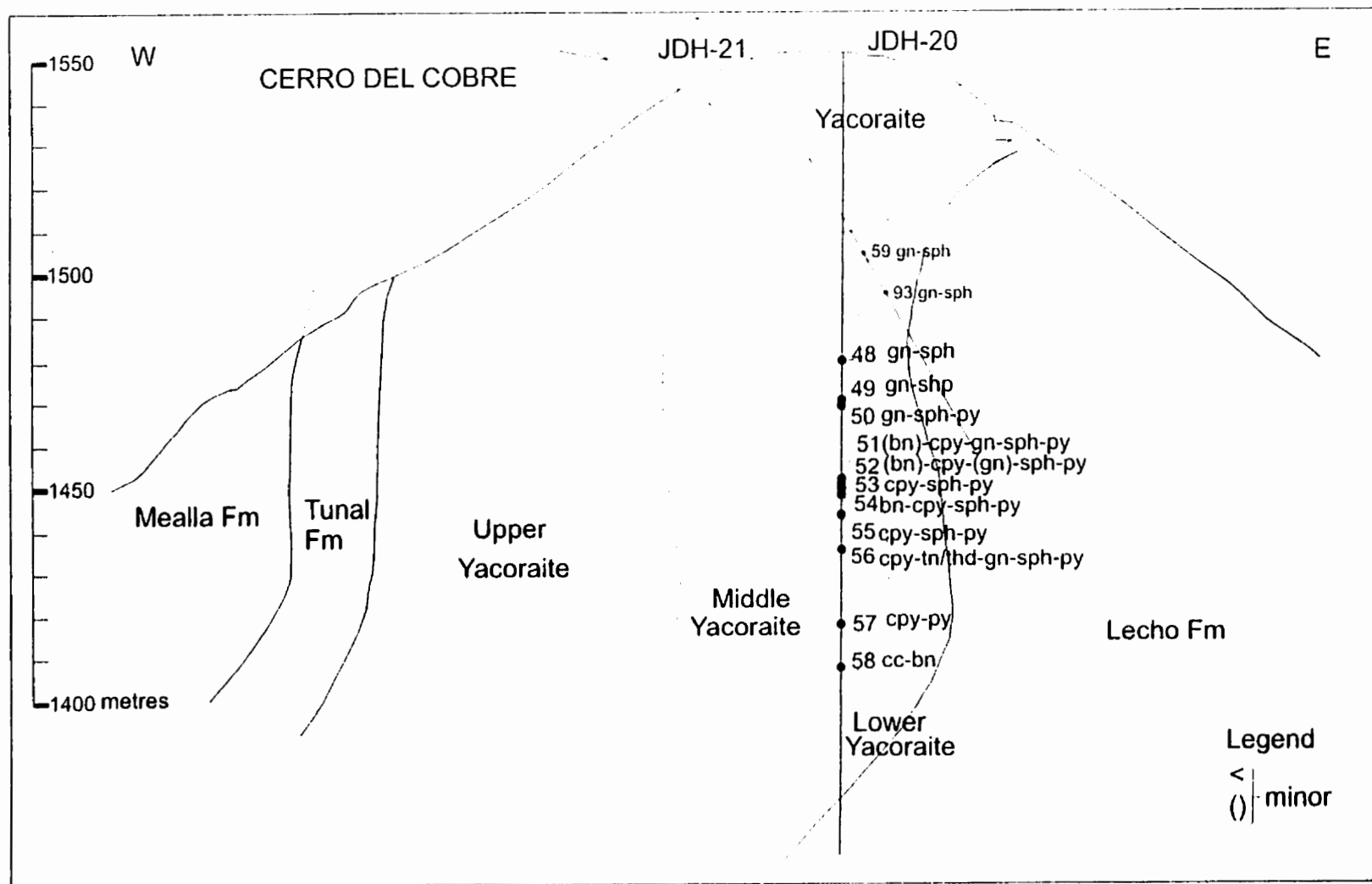


Figure 5.22: Schematic cross-section in line d-d' ( see Figure 2.7) showing drill hole JDH-20, the main stratigraphy and the sulphide zonation present. Samples from drill hole JDH-21 were plotted to assist the interpretation of zoning. Geology modified from Rotzien and Wormald (1998).

at the base of the copper zone, whereas the iron-rich cupriferous sulphide (chalcopyrite) becomes more common toward the passage to the other base-metal sulphide zones (lead and zinc zones). The sulphosalt, tennantite-tetrahedrite, coincides mostly with the transition between the iron-bearing copper sulphides and lead-dominant zones: it is a common associate of galena and chalcopyrite.

Thus, the zonation generally consist of copper-sulphide in a basal position, with lead- and zinc-sulphide zones progressively higher or laterally along and across stratigraphy. Combining the apparent vertical and lateral zonings and the relative two-dimension scales of these zonings, the overall zoning appears to be moderately transgressive to bedding. The limited lateral extent of the Juramento mapping and drilling, as well as obvious structural complexities and the alteration of sulphides on surface exposures, do not permit a more exact definition of the property-scale zoning.

#### **5.4 Supergene Oxide and Sulphide Mineralization**

Supergene oxide and sulphide mineralization at Juramento is observed down to an average depth of 70 metres at Juramento. The intensity of alteration is coincident with the apparent porosity of the rock and the presence of a gypsum cement filling the porosity. The supergene oxide mineralization consists of copper carbonates (especially malachite and azurite), lead and zinc carbonates (e.g., cerussite and smithsonite) and iron and manganese oxides (e.g., limonite, hematite and pyrolusite). Secondary sulphides include digenite and covellite.

Manganese oxides such as pyrolusite are readily seen on thin bedding laminations, especially with dendritic patterns on outcrops. Iron oxides and hydroxides are visible in thin sections associated with replaced cupriferous, lead, zinc and iron sulphides. They

are also present in voids left by former cubes of pyrite. In a few cases, unaltered pyrite was seen inside allochems on outcrops (e.g., at Cerro del Plomo).

#### 5.4.1 Malachite and Azurite

Malachite replaces copper sulphides in the upper parts of Cerro del Cobre and Cerro del Plomo, staining outcrops with a characteristic green colour. It fills open spaces produced by the dissolution of the cement in some grainstones. It is also found as rims surrounding grains of chalcocite, bornite and chalcopyrite exposed on surface (Figs. 5.23 and 5.24).

Azurite (Fig. 5.25) is also found in the supergene alteration zone, indicating a hot arid environment relative to malachite. It is commonly present as isolated idiomorphic crystals or aggregates in open spaces. The size of crystals rarely surpasses 0.3 mm.

#### 5.4.2 Cerussite-Smithsonite

Heavily-mineralized lead- and zinc-bearing horizons originally hosting a galena-sphalerite assemblage on Cerro del Cobre are overprinted near surface with a secondary porosity that allowed both dissolution and oxidation. The lead and zinc sulphides are replaced by carbonates (anglesite, cerussite and smithsonite) which fill voids caused by dissolution (Fig. 5.26).

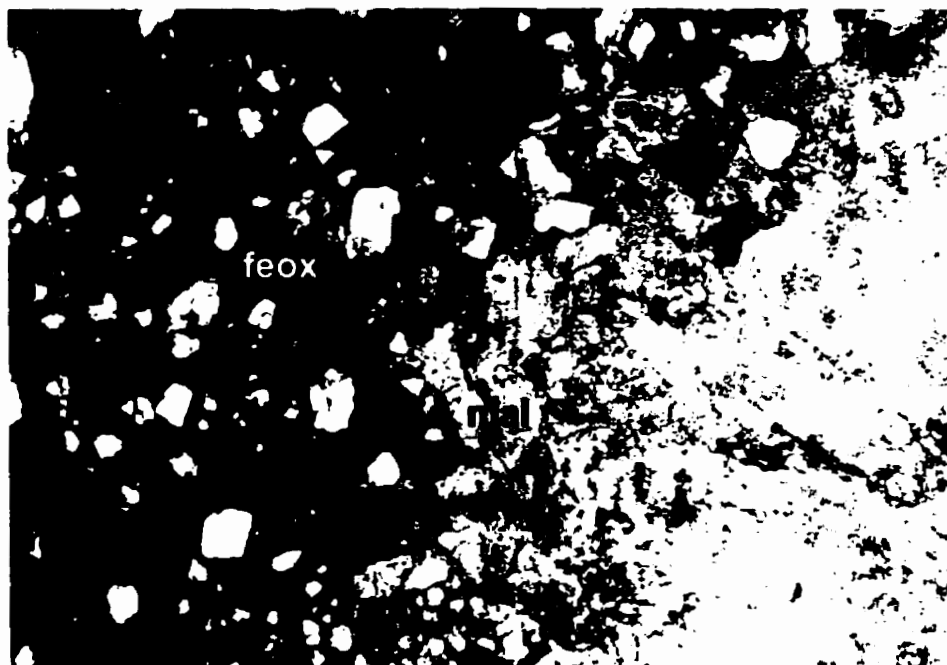


Figure 5.23: Malachite (mal.) developed in dissolution voids. Note the fibers in a botryoidal-like mass. Note also the presence of iron oxides (feox) as a cement in the dissolution cavity. Sample 1, PTS, PPL, FOV= 1 millimetre.

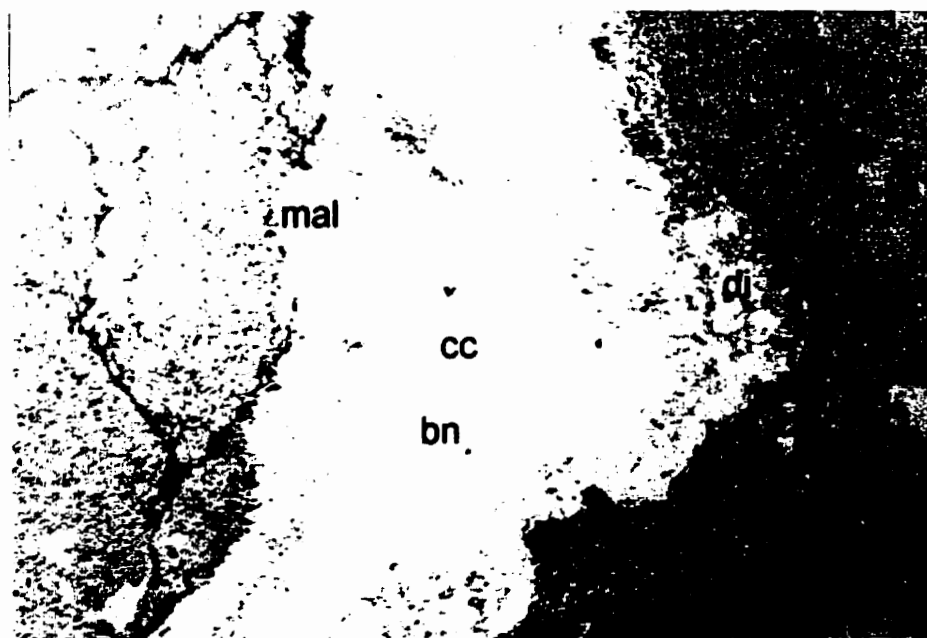


Figure 5.24: Malachite (mal, light blue) replacing a chalcocite (cc)-bornite (bn) grain. Note the presence of covellite (cv) and digenite (di) within the copper carbonate rim. Sample JPS 3, PS, RL, FOV= 0.87 millimetre.



Figure 5.25: Azurite stain in an intraparticle space of a grainstone. Note the association with iron oxides. Sample JDH-08-5, PTS, PPL, FOV= 1 millimetre.

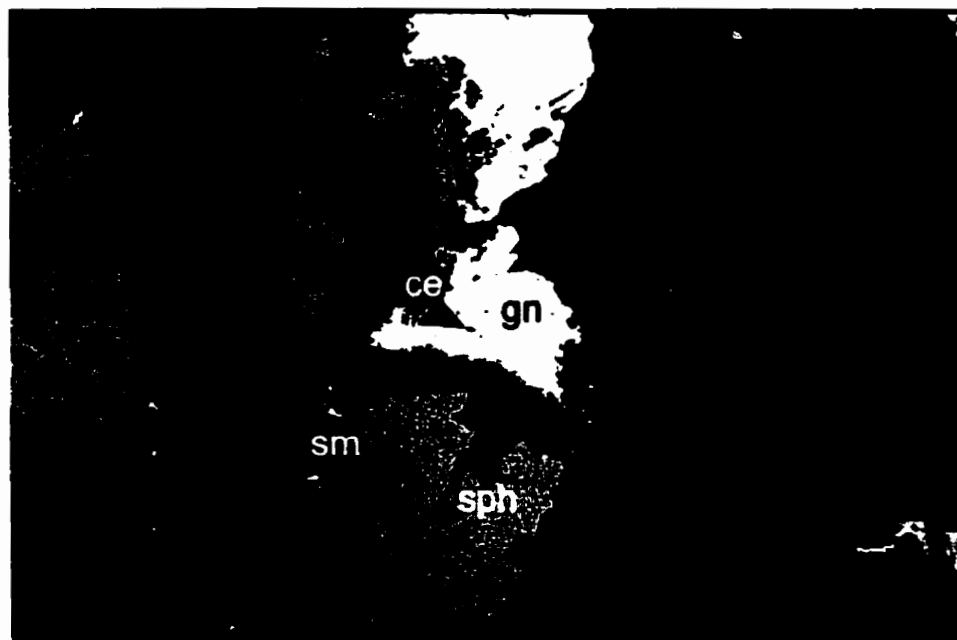


Figure 5.26: Cerussite (ce) and smithsonite (sm) partially replacing galena (gn) and sphalerite (sph) in a grainstone. Note the lighter color of the lead and zinc carbonates with respect to the ooids. Sample 59, PTS, RL, FOV=0.87 millimetres.

### 5.4.3 Covellite and Digenite

These supergene minerals were observed both in the oxide zone and in the immediately underlying sulphide zone.

Covellite, observed in minor to major amounts in many drill holes, forms veins across and rims around primary cupriferous sulphides such as chalcocite and bornite of the sulphide zone (Fig. 5.27) and it also occurs within rims of copper carbonates surrounding remnant copper sulphides in the oxide zone, suggesting that it preceded the formation of the copper carbonates (Fig. 5.24).

Digenite is observed only in samples from areas immediately below the oxidation zone where it forms rims around primary sulphides such as bornite and chalcopyrite, and overgrowths on sphalerite and galena (Fig. 5.28 and 5.29). The observed covellite rim texture to only relatively modest drill intersections below the oxidation zone suggests relatively moderate supergene alteration in the Juramento area.

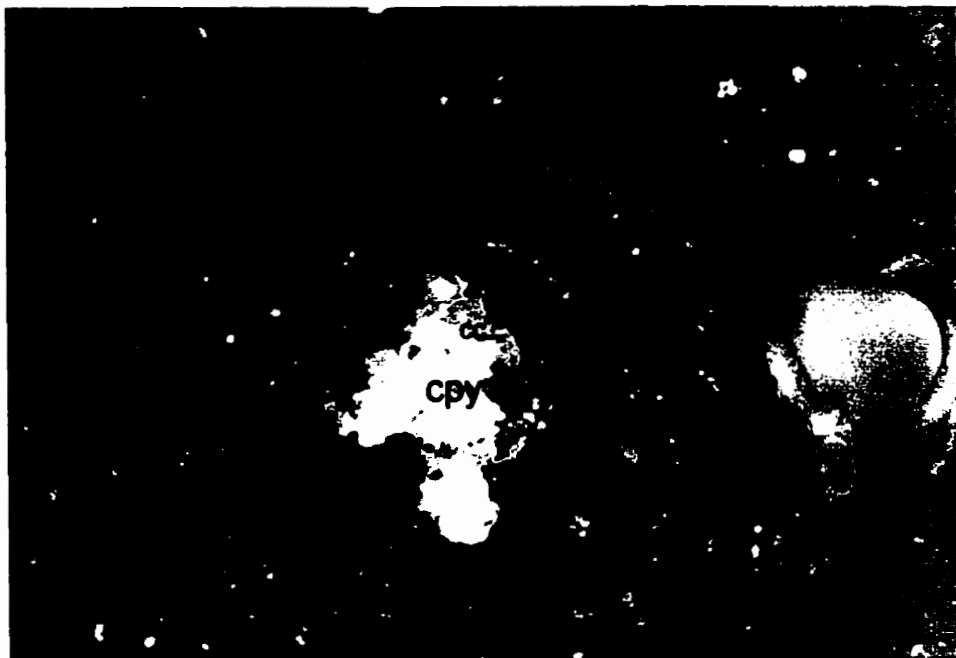


Figure 5.27: Covellite (cv, dark blue) replacing chalcocite (cc) and chalcopyrite (cpy). Note the presence of disseminated fine-grained pyrite in the matrix and inside the allochems. Sample 17, PTS, RL, FOV=0.2 millimetre.

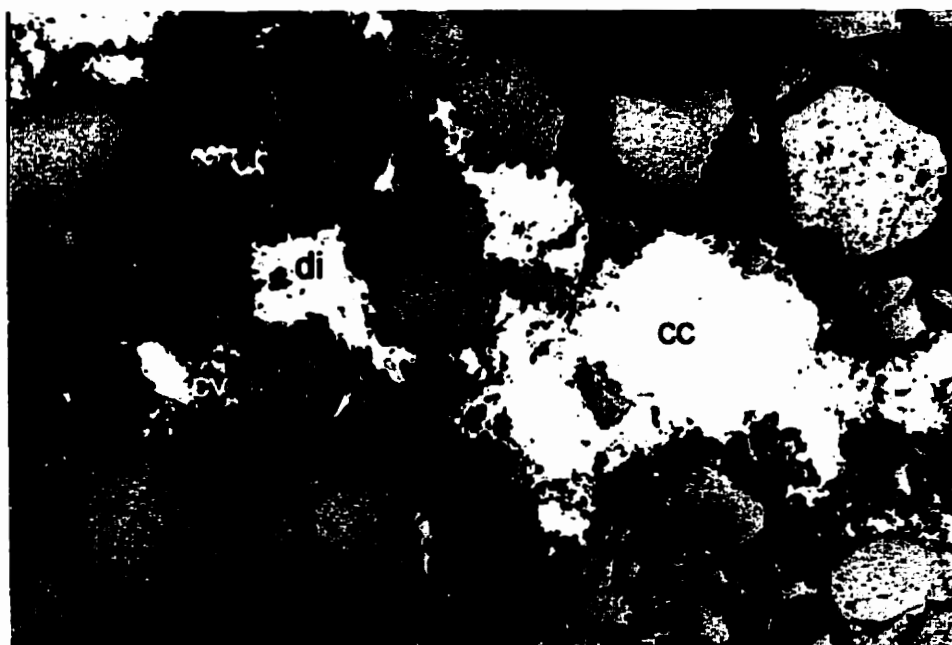


Figure 5.28: Digenite (di) and covellite (cv) replacing chalcocite (cc). Note the bluish colour of the digenite with respect to chalcocite and the dark blue covellite rim around the chalcocite and digenite grains. Sample 2, PTS, RL, FOV= 2 millimetres.



Figure 5.29: Digenite (di) replacing pink bornite (bn). Note the disposition of bornite in layers between cortices in an ooid. Sample 31, PTS, RL, FOV=0.5 millimetre.

## **CHAPTER 6**

### **DISCUSSION**

#### **6.1 Geology and Diagenesis of the Sedimentary Basin**

Much of our interpretation of the Juramento copper deposit is based upon its sedimentary context. With this in mind, the following discussion presents a summary of the environment of initial sedimentation, followed by the progressive diagenesis of the sediments, including the emplacement of its copper-dominant mineralization.

As shown in Chapter 2, the Juramento deposit is hosted principally by the carbonaceous calcareous sediments of the Yacoraite Formation, a sedimentary unit deposited in shallow marine or saline lacustrine waters; a minor portion occurs in the immediately adjacent Lecho Formation (Marquillas, 1984; Palma, 1984, and Marquillas and Salfity, 1988). The Yacoraite and Lecho sediments stratigraphically overlie redbeds of the Pirgua Formation which is composed mainly of reddish conglomerates and sandstones deposited in a rift basin under a warm and arid climate (see Chapter 2 and Chapter 3).

The occurrence of a carbonaceous unit (greybeds) overlying large volumes of immature continental clastic sediments (redbeds) is significant because of the capacity for oxidizing chloride brines in the redbeds to carry copper while reducing sulphide-rich conditions in the greybeds are suitable for copper sulphide deposition (Rose, 1989). The same fundamental stratigraphic units and tectonic settings can be found in many districts known for sediment-hosted stratiform copper deposits (SHSCDs). For example, for the

greybed-redbeds couplet, one can read of the Lower Zechstein and Rotliegende in the Kupferschiefer district (Rentzsch, 1974; Jowett, 1986, 1987), the Nonesuch Formation and the Copper Harbour Formation for the White Pine deposit (White and Wright, 1954, 1966; Brown, 1971), the R.2 (Groupe des Mines) and R.1 (R.A.T. rouge) in the Shaban-Zambian Copperbelt (Bartholomé, 1974; Cahen, 1974; Fleischer et al. 1976), and the Transition Zone and the Redstone River Formation in the Redstone (Coates Lake) deposit (Jefferson, 1978; Chartrand, 1981; Ruelle, 1982; Chartrand and Brown, 1985). In all of these examples and more, reducing conditions prevailed in the stratigraphically higher greybeds, and oxidizing conditions prevailed in the underlying redbeds.

Although considerable variation exists among the host-rocks for sediment-hosted stratiform copper deposits, the Yacoraite unit shares with other copper deposits of this type the essential characteristic of being a reduced greybed that acted as a chemical receptor for imported metals, as suggested in the general genetic models for sediment-hosted stratiform copper deposits described in the modern literature (for example, Gustafson and Williams, 1981; Haynes, 1986; Kirkham, 1989; Brown, 1992, 1997).

#### 6.1.1 Environments of Deposition of the Host-Rocks

Because host-rock preparation is an important factor for the precipitation of metals from the ore fluids and because this preparation is a function of the environment of deposition, we now discuss the probable environment of deposition of the Juramento host-rocks, based on our observations and on descriptions of similar environments elsewhere.

Although The Yacoraite Formation is generally known as a simple carbonate unit, in fact, in the Juramento area, this unit possesses several specific rock types that vary from

high-energy carbonates (e.g., grainstones and packstones) to low-energy carbonates (e.g., wackestones and mudstones) and siltstones (see Chapter 3).

The high- to low-energy calcareous sediments, as well as the siltstones show a particular apparent vertical arrangement across the stratigraphic column at Juramento. For instance, high-energy and low-energy calcareous sediments are abundant and thick at the base of the Yacoraite Formation whereas they are less common and less important higher in the stratigraphy where clastic sediments become dominant (see Fig. 2.8).

Examined more closely, the Yacoraite sediments exhibit other apparent vertical variations. For instance, oolitic-oncolitic grainstones and packstones with cross-bedding typical of moderate to high-energy and wave-dominated environments (Greensmith, 1989) lie in most cases on top of low-energy carbonates (Fig. 6.1).

Low-energy carbonate are composed mainly of wackestones and mudstones. The mudstones are commonly burrowed, a feature most likely formed within calm or restricted environments such as those found in lagoons or at levels beneath wave action (Greensmith, 1989). Because the allochems of some wackestones are oncoids or concentric algal concretions, a lagoonal environment with only slightly agitated water is more probable, probably located behind a protection barrier (e.g., sand bars) where biological activity is high. The fine parallel-laminated nature of the mudstones also suggests deposition in calm and/or restricted environments.

Clastic sediments are also important in the Yacoraite stratigraphic column, especially towards the upper Yacoraite. In the lower Yacoraite where clastic sediments are rare, the siltstones are mainly fine parallel-laminated and the principal grain size is a very fine silt associated with organic matter-rich laminae. These siltstones are generally overlain by low-energy calcareous sediments and form the base of built-up sedimentary cycles,

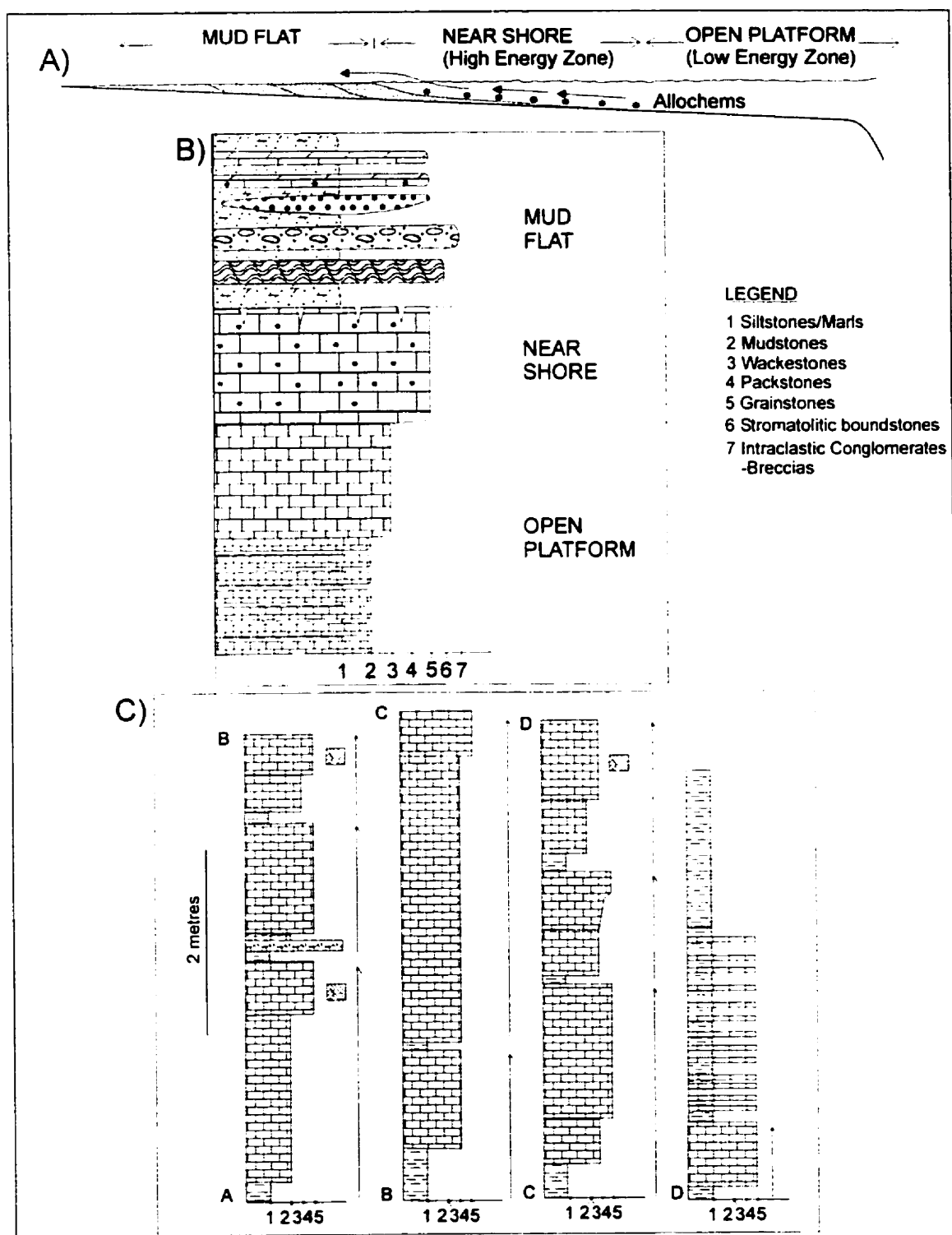


Figure 6.1: Shallowing-upward sequence. A - Sketch of the environments of deposition for a theoretical shallowing-upward sequence (modified after James, 1984). B - Schematic shallowing-upward sequence for Juramento, see text for discussion. C - Interpreted shallowing-upward sequences (arrows) in the vicinity of the Leon adit.

beginning with sedimentation in a very calm environment such as an open platform (James, 1984).

Siltstones from the middle and upper Yacoraite are slightly different from those of the lower Yacoraite. They are associated with stromatolites (or fine calcareous laminations interpreted to be of algal origin), intraclastic conglomerates and oolitic bars. Gypsum nodules are also common in the upper Yacoraite. Grain sizes are variable and, in some cases, they attain coarse silt size. These coarser sediments suggest a high-energy calcareous sediments interpreted as having formed in shore or near-shore, clastic-dominated environments. They could have been deposited on mud flats or flood plains (Platt and Wright 1991) with associated algal mats. In this case, sporadic storms would be responsible for the allochthonous sediments such as oolitic bars and intraclastic conglomerates.

Thus, the Yacoraite Formation is characterized by both high-energy and low-energy environments. In general, these contrasting end members are arranged in sequences with passages from low- to high-energy environments in which the pelagic clastic sediments and low-energy carbonates are followed upwards by high-energy limestones and later by shoreline or flood plains clastic sediments.

These characteristic shallowing-upward sequences would have formed on stable carbonate platforms (Friedman and Sanders, 1978; James, 1984; Tucker and Wright, 1990; Friedman et al., 1992) where the rates of sedimentation are greater than the rate of subsidence (James, 1984) and where successive sediments are deposited in progressively shallower waters.

Such shallowing-upward sequences are found in lacustrine low-gradient ramp margins (Tucker and Wright, 1990), as in the lacustrine Eocene Green River Formation in the

western United States (Williamson and Pickard, 1974) and in the modern lake sediments of the East African Rift (Kendall, 1969; Readings, 1982; Platt and Wright, 1991).

These basin environments are paralleled in the Juramento area by two positive elements in the northwestern portion of the Metan sub-basin (see Fig. 2.6); one is a swell (basin high) and the other is the margin of the Salta-Jujuy high. The Salta-Jujuy high slowly subsided during Cretaceous time and acted as a stable platform throughout the existence of the Salta Basin (Marquillas and Salfity, 1988).

Our study of the Juramento sediments suggests as well that sediments of the upper Yacoraite occurred without need for tectonic control on sedimentation and facies location. That control would have been an environmental control on the water level, allowing clastic sediments to progress and to become dominant over the calcareous sediments.

Amengual and Espisúa (1983) described the Juramento rocks as having been deposited in a sabkha environment, but gave few details to support their interpretations. For example, there is no direct evidence of extensive evaporitic beds in the Yacoraite, at least in the Juramento area. However, gypsum laths served as an early cement in oolitic grainstones and gypsum nodules are common in the upper Yacoraite.

More complete and detailed descriptions of the sedimentology of the area are discussed by Marquillas (1984a, 1986) (Chapter 2) for a sector approximately 15 km to the southwest of Juramento. After descriptions of the rocks types and their relative locations, Marquillas made a statistical analysis of the frequency of sedimentological transitions, and found a cyclicity in sedimentation. Cycles begin with low-energy sediments (mudstones and wackestones) that evolve upward towards high-energy ones (grainstones and packstones), as seems to be the case for the Juramento area (see above).

Palma (1984) did work similar to that of Marquillas but in the northern portions of the Salta-Jujuy high (in the Tres Cruces sub-basin; Fig. 2.5) and found the same suite of sediments and transitions as Marquillas. He also found that the sediments were deposited both in low-energy near-shore environments and in moderate to high-energy (i.e., wave-dominated) transitional environments, and in accordance with variations of water level in the upper Yacoraite. Based on sedimentological and faunal evidence, Palma concluded that the sediments of his study area are lacustrine. In addition, he described the Tunal Formation as a fluvial-dominated flood-plain sediment.

Camoin et al. (1994) worked on the El Molino Formation in the Central Andean Basin of Bolivia (Fig. 2.5). They agree with the facies model presented by Palma and suggest that the sediments represent an open perennial lake during the deposition of the Lower El Molino Formation and an ephemeral lake for the Upper El Molino Formation. For the Lower and Middle El Molino Formation, they described the same lacustrine facies as Palma described for the Yacoraite Formation. They also concluded that, in the case of the Upper El Molino Formation, flood-plain and shallow-water calcareous sediments were deposited in an ephemeral lake environment. In this stratigraphic portion of the El Molino Formation, they also noted evaporites (sulphates and chlorides) towards the centre of the basin.

In addition to similarities between the stratigraphic sequences at Juramento and the strata described by Marquillas and Palma in other sectors of the basin, and by Camoin in other portions of the Cretaceous rift, we can add important sedimentological features that seem to support the Juramento section as shallow marginal lacustrine sediments. For example, the oolites which form grainstones and packstones in the Yacoraite Formation are large compared with oolites forming in the modern marine environment of the Bahamas (Tucker and Wright, 1990); at 0.7 to 1.2 mm in size, they are two to

three times larger than bahamites. Also, the Yacoraite oolites typically have radial cortices likely to have formed in saline lakes where the cortex-forming mineral is aragonite; a modern example of lake-type oolites is found in the Great Salt Lake of Utah (Eardly, 1966; Sandberg, 1980; Dean and Fouch, 1983). Large lakes of this type tend to form in intracratonic rift basins, such as those of the Basin and Range Province and of the East African rift (Tiercelin, 1991).

Such tectonic settings would be appropriate for deposition of the Yacoraite sediments. Moreover, the finely and evenly laminated, organic matter-rich stromatolites found at Juramento are characteristic of the near-shore facies of saline lakes (Tucker and Wright, 1990) and they resemble those of the lacustrine Eocene Green River Formation of the western United States (Hoffman, 1997, personal communication). In addition, charophytes found at Juramento and in other areas of the Salta basin are typical of lake sediments (Mussacchio, 1972; Palma, 1984; Marquillas 1986).

However, there is a lack of extensive evaporitic sediments in the Juramento area. If such sediments existed possibly they were removed in the vadose environment. Nevertheless, it is common to see displacive gypsum nodules in the siltstones in the upper Yacoraite: in some cases, the nodules are replaced by quartz (see "Syndiagenesis" below). It is also notable that in this siltstone section the dominant sediments are flood-plain deposits rather than carbonates. The latter would be characteristic of a low-energy shoreline environment where stromatolites could be common.

In summary, the rock types of lower Yacoraite in the Juramento area are similar to marginal sediments deposited on a low-gradient ramp with coastal (probably lacustrine) and continental influence.

### 6.1.2 Syndiagenesis

In this and the following two sections ("Early Diagenesis" and "Late Diagenesis"), we discuss various stages of diagenesis in some detail because they involve several fundamental events and processes crucial to the preparation of the host sediments for mineralization and crucial also at the moment of copper emplacement. Among topics discussed are: 1) the preservation of organic matter and its degradation, to assure reducing conditions within the Yacoraite sediments; 2) the formation of post-sedimentary pyrite; 3) the preservation and creation of sediment porosity; and 4) the influx of (Cu-Pb-Zn-Ag)-bearing fluids resulting in the Juramento mineralization.

Post-sedimentary time is divided into the following progressively more advanced intervals within the evolution of the Salta basin and sub-basins: 1) syndiagenesis, 2) early diagenesis, 3) late diagenesis, 4) tectonic overprinting and 5) supergene alteration (See Fig. 6.2). Emphasis is given to time rather than space during this progressive diagenesis because our observations are limited mostly to the Juramento property and are not sufficiently widely distributed across the Salta Basin to comment on regional aspects.

Several processes and events are included in the present section under the title of "syndiagenesis", those having occurred within centimetres of the active sedimentary surface. Under this heading, we discuss: 1) gypsum precipitation, 2) micritization, 3) pyrite formation, 4) early cements, and 5) dolomitization.

The two forms of gypsum are found in the Yacoraite Formation: gypsum laths and gypsum nodules. In some oolitic grainstones of the lower to middle Yacoraite, former gypsum laths are found in intergranular spaces, indicating porosity was high; this gypsum precedes the filling of pores by micritic cement (Fig. 4.27). Meanwhile, in the

|                                           | Syn-diagenesis | Early Diagenesis | Late Diagenesis | Tectonic Overprinting | Supergene Alteration |
|-------------------------------------------|----------------|------------------|-----------------|-----------------------|----------------------|
| Gypsum I                                  | —              |                  |                 |                       |                      |
| Micritization                             | —              |                  |                 |                       |                      |
| Pyrite                                    | —              |                  | —               |                       |                      |
| Dissolution                               | —              |                  |                 |                       |                      |
| Calcite Cement:<br>Meniscus<br>Isopachous | —              |                  |                 |                       |                      |
| Dolomitization                            | —              |                  |                 |                       |                      |
| Packing                                   |                | —                |                 |                       |                      |
| Early Fractures                           |                | —                |                 |                       |                      |
| Cement II                                 |                | —                |                 |                       |                      |
| Mineralization                            |                | —                |                 |                       |                      |
| Silica/K-spar                             |                | —                |                 |                       |                      |
| Compaction                                |                |                  | —               |                       |                      |
| Dolomite II                               |                |                  | —               |                       |                      |
| Calcite<br>Recrystallization              |                |                  | —               |                       |                      |
| Stylolites                                |                |                  | —               |                       |                      |
| Late Fractures                            |                |                  |                 | —                     |                      |
| Cement III                                |                |                  |                 | —                     |                      |
| Hydrocarbons                              |                |                  |                 | —                     |                      |
| Dissolution                               |                |                  |                 |                       | —                    |
| Gypsum II                                 |                |                  |                 |                       | —                    |
| Supergene<br>Alteration<br>Minerals       |                |                  |                 |                       | —                    |

Figure 6.2: Summary of the diagenetic events affecting the Juramento host-rocks. See text for discussion.

calcareous siltstones and pelrites of the Upper Yacoraite, gypsum nodules show displacive growth textures in which growth occurred in association with surface evaporation and before important compaction by overlying sediments (Figs. 4.20 and 4.30). Therefore, gypsum laths and gypsum nodule precipitation are interpreted to be syndiagenetic, probably having occurred very shortly after deposition of the sediments and during periods of subaerial exposure.

Micritization is an omnipresent process in some of the Yacoraite limestones at Juramento (Figs. 3.9, 3.11 and 4.2). It is produced by endolithic (boring) micro-organisms such as cyanobacteria, algae or fungi (Tucker and Wright, 1990). Thus, micritization accompanies abundant organic activity. Occurring immediately below the water/sediment interface, this process is interpreted as syndiagenetic. It is probably contemporaneous with pelloid formation, during which period organic activity is high (Wolf, 1965; Friedman, 1973).

Extensive bacterial activity during syndiagenetic time would also have been suitable for the precipitation of pyrite under reducing conditions. Two textures of pyrite are observed: 1) pyrite after gypsum laths, and 2) disseminated pyrite. Pyrite pseudomorphs after gypsum laths has been totally to partially replaced by chalcopyrite in some horizons of the lower Yacoraite Formation (Fig. 4.27), but remnants of pyrite in gypsum laths was seen in one sample. Most likely, this pyrite resulted from the direct anaerobic bacteria reduction of the sulphate of gypsum laths. In addition, anaerobic bacteria feeding on organic debris would reduce dissolved sulphate available in the interstitial pore fluids, leading to the precipitation of pyrite (Figs. 4.21, 4.22, 4.24 and 4.25). Thus, both forms of pyrite are interpreted to be bacteriogenic and to have formed close to or at the active depositional surface, as described by Tucker and Wright (1990).

Another syndiagenetic event consisted of the development of a secondary porosity

closely associated with the micritization; micritic boxes around pelecypods and gasteropods shells are found to be the only remnants of these allochems after selective dissolution and the formation of secondary porosity (Fig. 3.9). The shells would have been dissolved in the vadose zone where the sediment comes in contact with  $\text{CaCO}_3$ -undersaturated water; later calcite is seen to fill moulds. This process is interpreted to be syndiagenetic, with dissolution occurring soon after micritization.

A subsequent calcitic meniscus cement is also interpreted to be a very early diagenetic (essentially syndiagenetic) feature, resulting from the precipitation of calcite in pores from a film of water wetting the pore walls (Figs. 3.9 and 4.2). This cement would typically precipitate in the vadose zone during very early diagenesis or during subaerial exposure of the sediment (Tucker and Wright, 1990; James and Choquette, 1990). This vadose event was probably closely coincident with the dissolution event (development of an early secondary porosity).

Another cement consists of a narrow fringe of isopachous calcitic cement (Figs. 3.6 and 3.8). This early cement would have been generated during sedimentation, before closure of the pores by equigranular cement. The isopachous cement is named first-generation cement and happened in high-energy limestones (mainly in oolitic grainstones) and demonstrates that the limestones were poorly cemented during this first stage of diagenesis. Marquillas and Matheos (in press) also found this feature during cathodoluminescence studies of grainstones in the San Pablo margins.

Dolomite in the Yacoraite sediments show that it preferentially replaced fine-grained calcareous sediments such as siltstones and mudstones, rather than grainstones and packstones. This dolomite is not well crystallized and is very similar to the micrite of bored mudstone. The fine-grained texture suggests a penecontemporaneous replacement of pre-existing fine-grained sediments, a texture distinctly different from the coarser grained euhedral crystals of dolomite formed during later burial diagenesis.

Intraclastic conglomerates also show clasts of fine-grained dolomitic mud, in which the clasts were dolomitized before transportation to their present site of sedimentation, also suggesting penecontemporaneous replacement (Fig. 3.21). These observations suggest very early dolomitization.

### 6.1.3 Early Diagenesis

We interpret early diagenetic to include processes that occurred without further influence from the depositional environment at the sediment-water interface. Early diagenesis probably extended from the first centimetres of burial down to a maximum of 100 metres (i.e., within a zone of shallow burial). Here we discuss: 1) sediment packing, 2) base-metal mineralization, 3) second-generation cement, and 4) silicification.

The packing of oolitic sediments is obvious from spalled cortices of concentric oolites. The absence of extensive cementation before this compaction would have allowed for deformation by compaction between a burial of a few metres to 100 metres, depending on the composition of the sediment and on the overburden charge (Choquette and James, 1990). It is also possible to see collapsed ooids which were partially dissolved before compaction, possibly during residence in the vadose meteoric zone and during the creation of an early secondary porosity.

Minor fracturing is also observed in some ooids which, after initially resisting the stress of moderate burial, gave way with brittle fracture to the increasing burial pressure. These fractures are nevertheless interpreted to have resulted during relatively minor compaction. After that packing and fracturing, the remaining pores and newly formed fractures were filled with a second-generation cement.

A second generation of coarse, equigranular, non-ferroan to slightly ferroan carbonate cement is observed in the Yacoraite sediments (Figs. 3.8 and 4.2). This cement, mainly found in grainstones, completed the filling of pores and the minor fractures in ooids, after the emplacement of the isopachous cement mentioned above. It also filled voids formed by dissolution of aragonitic shells (Fig. 3.9). This cementation took place before advanced compaction and deep burial, during which voids would already have collapsed at depths exceeding approximately 100 metres (Choquette and James, 1990). Marquillas and Matheos (in press), using cathodoluminescence, found the equivalent cement in high-energy sediments of the Yacoraite Formation; they identify it as second-generation cement and interpreted that cement as early diagenetic too.

Silicification, pervasive during early diagenesis, consists of the deposition of authigenic quartz, microquartz and chalcedony. Dolomitized ooids and sulphide grains are enveloped by microquartz that occupies the pore spaces around them (Figs. 4.10 and 4.18). Also, chalcedony is present in intercrystalline spaces between rhombohedra of dolomite in dolomitized low energy sediments (Fig. 4.11). Silicification is then interpreted to have occurred after dolomitization and pyritization and also to have completely sealed the porosity in some cases.

In other cases, detrital grains of quartz show overgrowths, resulting in euhedral quartz grains (Figs. 4.14, 4.15 and 4.16). In turn, the overgrowths preferentially penetrate the cortices of some ooids (Figs 4.15 and 4.16), but do not replace the micritic cement. This texture suggests that silica preferentially replaced unstable aragonite before its modification to the more stable calcite (high- and low-Mg sub-types). This emplacement of quartz is interpreted as early diagenetic. Hesse (1987) found similar textures for the sediments of the Lower Cretaceous Gault Formation of the eastern Alps and interpreted the silicification to be early diagenetic and contemporaneous with selective dissolution of carbonate.

In addition, silicified oolitic grainstones with cores replaced by microquartz as well as authigenic quartz overgrowth show high resistance to deformation by compaction. Other deformed or collapsed (i.e., previously dissolved) ooids or pelloids do not show silicification, and therefore silicification is also interpreted to have happened before the advanced compaction of late diagenesis.

It is also possible to constrain the mineralization at Juramento to an early diagenetic timing. First, the cleavage seen in some galena grains demonstrates that this mineralization was present prior to the uplift and deformation of the Andean Orogeny (Inca phase see Chapter 2). Second, as discussed above, pyrite preceded silicification, and base-metal sulphide mineralization is seen to replace this early formed pyrite. These observations restrict the timing of base-metal mineralization between syndiagenesis and much later tectonism.

However, additional constraints maybe imposed on the timing of mineralization. For example, chalcopyrite forms pseudomorphs after gypsum laths in oolitic grainstones. In the same sample, many ooids show advanced deformation; however, the replaced laths are not highly deformed as might be expected from advanced compaction. In some cases, the replaced laths even interpenetrate ooids. In addition, some mineralization hosted by grainstones occupies intergranular porosity and does not show closure of pores by a second-generation dolomitic cement.

It is also possible to observe grains of chalcopyrite hosted in a dolomitized and silicified wackestone, in such case the sulphide grain was surrounded by authigenic quartz. The authigenic quartz was also observed to be present in the intercrystalline spaces of dolomitic grains. Mineralization can then be designated as early diagenetic and is interpreted to have arrived between dolomitization and silicification and prior to strong compaction.

#### 6.1.4 Late Diagenesis

After early diagenesis, as pressure increases under more advanced burial, we see 1) emplacement of second-generation dolomite, 2) recrystallization of calcite, and 3) the formation of stylolites. These effects are attributed to late diagenesis which probably extended until the reversal of the basin during the Inca tectonic phase at the Paleocene-Eocene transition.

The coarse-grained euhedral ferroan dolomite in the Yacoraite sediments is interpreted to have formed by recrystallization of the fine-grained dolomite discussed above. The coarse-grained subtype is consistently in contact with fine-grained dolomite and in some cases it forms patches in areas where fine-grained dolomite is dominant. Also, fine-grained dolomite is seen as trapped inclusions in the coarser dolomite (Fig. 4.9).

Calcite recrystallization is observed in the cortices of ooids (Fig. 3.5) and microspar is present in a few samples, probably due to recrystallization of the micritic matrix (Figs. 3.12 and 4.7).

Abundant sutured and non-sutured stylolites are also characteristic of this stage of diagenesis in the Juramento host-rocks (Figs. 4.7 and 4.13). They are developed during burial at depths of at least 500 (Dunnington, 1967; Mountjoy, 1999, personal communication) and are interpreted here as the latest stage of diagenesis recorded in the Yacoraite Formation. This diagenesis ends with the beginning of tectonic deformation which was probably caused by the reversal of the basin (see Chapter 2). It is notable that the stylolites at Juramento were initially mistaken for vein-like mineralization, and were interpreted to post-date the formation of hydrocarbons, leading to confusion with respect to the timing of copper-(silver) mineralization.

The stylolites at Juramento tend to concentrate relatively insoluble minerals such as quartz and feldspars as well as organic matter and sulphides. Much of the quartz is euhedral and had formed during silicification prior to stylolitization. They also concentrated organic matter and sulphides.

#### 6.1.5 Tectonic Overprinting

Several processes resulted from the uplift and deformation associated with the Andean Orogeny: 1) second-generation fracturing, 2) third-generation cementation, and 3) the introduction of hydrocarbons.

Second-stage fractures are found across the entire Yacoraite stratigraphic section at Juramento. These fractures post-date all previously described diagenetic effects. The fractures are filled by a third-generation cement consisting of relatively coarser grained (20 to 30  $\mu\text{m}$ ) ferroan calcite (Figs. 3.10, 4.3 and 4.17).

Hydrocarbons are systematically associated with second-generation fractures (Fig. 4.34). The hydrocarbons are soft (i.e., tar-like) and do not show high reflectances, as would be expected had they been present in the sediments before deep burial. Thus, they are interpreted to be late introductions to the host-rocks, at least in the Juramento area. Mon and Salfity (1995) also noted a tectonic (fracture-controlled) timing for hydrocarbons in the Yacoraite sediments of the Sub-Andean ranges.

### 6.1.6 Supergene Alteration

After uplift, the Yacoraite sediments were weathered when and where they were exposed to meteoric conditions which still continue in the area. Here we discuss: 1) second-generation gypsum, and 2) supergene alteration minerals.

Second-generation gypsum coincides with the supergene alteration zone; as described in chapter 3, gypsum fills late (modern) dissolution cavities (Fig. 4.30). It is possible that such a porosity was created by dissolution due to the circulation of meteoric water before or during this later deposition of gypsum. The sulphate may have been resulted from the weathering of sulphides. Weathering of iron sulphides is well-known to produce sulphuric acid which would readily dissolve the carbonate host-rock.

Copper carbonates, iron oxides and manganese oxides are associated with supergene alteration (see chapter 5). This event is the last (and on-going) process affecting the Juramento host-rocks.

## 6.2 Mineralization

As noted in the previous sections, base-metal mineralization is interpreted to have been early diagenetic at Juramento. We now discuss the emplacement of this sulphide mineralization in greater detail, concentrating on the minerals of the primary sulphide zone. The approach taken in this discussion is to review our descriptions in prior chapters and to present those features in the form of a general genetic model for the Juramento deposit. The model begins with host-rock preparation.

The Yacoraite Formation was initially prepared chemically for mineralization due to the

formation of syngedimentary and syndiagenetic reducing conditions assured by the abundance of organic matter found in platform carbonates (e.g., algal matter). That the carbonates were lacustrine or marine is immaterial to our chemical model, but we conclude from our observations and their similarities to others that in fact the conditions were most probably lacustrine. In the presence of abundant organic matter, anaerobic bacteria would have thrived and reduced important amounts of sulphur from sulphate to sulphide. The sulphate was probably derived in part from sulphate diffusion downward from the overlying evaporitic lacustrine water (giving rise to disseminated syndiagenetic pyrite, including framboidal pyrite) and in part from gypsum recently precipitated from that water (resulting in replacements of gypsum laths by pyrite). The iron necessary to precipitate the bacteriogenic sulphide as pyrite may have been derived from the ferruginous detritus in carbonate rocks.

The Yacoraite must also have been prepared physically for mineralization. For example, the carbonate would need to have been at least moderately permeable at the time of diagenetic mineralization. We observe that the sediment remained porous at least until early diagenetic time, but became much more closed or sealed both by compaction and cementation as diagenesis advanced towards late diagenesis. In fact, the textural evidence of base-metal sulphide deposition places the introduction of base-metal before sealing by silicification.

Thus, the timing of mineralization is satisfactorily explained by an early diagenetic influx of ore-forming solutions. If this perspective is correct, then it is to be expected that the base-metals would exhibit a zoning of base-metal (Cu-Pb-Zn) sulphides with the more soluble sulphide further "downstream" than the less soluble ones. In addition, if pyrite and gypsum are the reactant for base-metal precipitation, as shown by replacement textures, then unreplaced pyrite and gypsum should be still further downstream. Furthermore, due to their relative solubilities, cupriferous sulphides

should be closer to the source of infiltrating ore solutions and lead and zinc sulfides progressively more distant from that source.

Our observations on the apparent zoning of base-metal sulphides in drill core at Juramento at least broadly confirm this perspective. In general, cupriferous sulphides are concentrated mostly near the base of the Yacoraite Formation (lower to middle Yacoraite), i.e., close to the redbed source of ore metals (see below). Pyrite, on the other hand, is predominant in the upper stratigraphic levels (upper Yacoraite), distant from the redbed source. Galena and sphalerite are mostly between the highly cupriferous basal strata and the unmineralized pyritic beds above. Silver-bearing sulphosalts are located in the interface between the cupriferous sulphides and the galena and sphalerite dominant zones.

In detail, this gross zoning is variable. In drill core JDH-25, the amount of galena and sphalerite is significantly more abundant than copper sulphides, but the copper sulphides are nevertheless concentrated at the base of the Yacoraite Formation, and the most copper-rich phase is chalcopyrite instead of bornite or chalcocite as seen in other drill holes. This distribution may be explained by a lateral component to the zoning. Lateral zoning is probably also visible to the south of drill hole JDH-25, where the sulphides seem to be laterally zoned along a single stratigraphic horizon.

The characteristic sulphide textures, timing, and zoning of the various sulphide species support an introduction of metals through the base of the Yacoraite Formation, largely perpendicular to bedding but with a modest departure from the perpendicular in order to account for the moderately transgressive nature of the zoning. The direction of inclination of the zoning cannot be determined due to the limited area investigated and to the structural complexity evident on the Juramento property. Although this study does not deal with a complete genetic model, the metal source could then be attributed

to leaching from the subjacent redbeds of the Pirgua Subgroup. The other essential constituent of the ore-forming solution would be a low-temperature brine. These brines could also have been derived from the Pirgua sediments, where evaporitic facies are common. The brines would then have equilibrated with the red-beds, thereby scavenging metals from the oxides and hydroxides surrounding detrital grains and/or leaching metals from the grains themselves (Walker, 1989). The brines could then have circulated through the basin (driven by hydrostatic pressure, for example) to enter and mineralize the sulphur-rich reduced Yacoraite Formation.

Sulphur isotopes analyses show that the pyrite from the Yacoraite Formation possesses normal light sulphur isotopes values. There is no apparently different values for the different pyrite textures. Most important, the observed fractionation in sulphur isotopes for pyrite is typical of bacterial reduction (Trudinger et al., 1985). Thus, most of the sulphur was reduced by bacteria feeding on organic matter or reducing sulphate from previously precipitated minerals such as gypsum, thereby transforming the Yacoraite in a readily source of sulphide to be used in precipitating the metals introduced by the ore-forming brine.

However, as a whole, the Cu-Pb-Zn sulphides and silver-bearing sulphosalts show a sulphur isotopic signature distinctly different from that of pyrite. These sulphides tend to be isotopically heavier than pyrite, including pyrite formed pseudomorphically after gypsum laths. Heavier sulphur isotopic values for the base-metal mineralization could be explained by contamination or addition of sulphur to the Yacoraite Formation by the mineralizing brines or connate waters. Additions of sulphur were demonstrated to be important by Hoy and Ohmoto (1989) for several other sediment-hosted stratiform copper deposits (e.g., Redstone and Kamoto). On the other hand, with the limited number of analyses available, it is difficult at this point to advance a plausible mechanism for sulphur additions and in situ reduction of sulphate from the ore solution

at Juramento. Such a reduction would require either an excessively high temperature (i.e.  $>250^{\circ}\text{C}$ ; Trudinger et al. 1985) or the presence of active bacteria at the time and place of introduction of a low-temperature brine. There is no evidence from our petrographic observations of temperatures exceeding  $250^{\circ}\text{C}$ , and the presence of significant bacterial activity after burial is also very speculative.

The host rocks at Juramento do not show evidence of exposure to high temperatures; however, certain sulphide textures suggest appreciable pressures and temperatures, presumably after the mineralization event. Exsolution textures found in pink bornites from Juramento suggest that mineralization initially happened at low temperatures (see chapter 5). Using the relation between events affecting the host rock, it is possible to constrain the timing of mineralization to an early diagenetic, pre-silicification timing, and before 500 metres depth of burial of the sediments. At such depths, the temperature during mineralization probably never surpassed  $75^{\circ}\text{C}$ .

## **CHAPTER 7**

### **CONCLUSIONS AND RECOMMENDATIONS**

Based on petrographic, mineralogic, textural and stratigraphic studies, the following principal conclusions can be drawn about the nature and origin of the Juramento sediment-hosted stratiform copper deposit:

- 1) The environment of deposition of the host rocks seems to be that of marginal lake sediments deposited under shallowing-upward conditions. Low-energy open-platform sediments account for the base of the sequence whereas high-energy calcareous sediments and mudflats or shore clastics form the uppermost sequence; between are low-energy calcareous sediments which had abundant organic activity.
- 2) Diagenetic processes that affected the host rocks at Juramento are interpreted to have been those normal for a marginal lacustrine sediment. Three periods of diagenesis and the overprints of two subsequent modifications are identified: syndiagenesis, early diagenesis, late diagenesis, tectonic overprinting and supergene alteration.
- 3) Mineralization is interpreted to have arrived, probably in a low-temperature chloride-rich brine, during early diagenesis (i.e., during shallow burial), between shallow syndiagenetic dolomitization and deeper silicification of the host rock. There is no apparent relation between mineralization and tectonism, other than the minor recrystallization with greater pressure at depth and the supergene alteration during near-surface weathering. Nor is there any obvious relationship of mineralization with

the introduction of hydrocarbons which was late diagenetic and related to deformation.

- 4) Primary disseminated ore-stage mineralization consist mainly of copper sulphide assemblages, such as chalcocite, bornite and chalcopyrite. Accompanying mineralization consist of galena and sphalerite. Silver is apparently present only in a sulphosalt (i.e., in tennantite-tetrahedrite) closely associated with chalcopyrite. Copper mineralization replaced the existing reduced sulphur (pyrite) in part; portions of pyrite remain in non-porous textural sites (e.g., in the well-sealed cortices of ooids). The assemblages and textures of sulphides, especially copper, suggest that mineralization occurred at low temperatures.
- 5) The metals are zoned, with the more copper-rich sulphide species concentrated near the base of the Yacoraite Formation, and more soluble metal sulphides (galena and sphalerite) generally higher stratigraphically and unreplaced pre-ore pyrite still higher yet; a minor peneconcordancy of sulphide zones is apparent. The position of the copper zone in the basal Yacoraite indicates that the ore-forming fluids entered from underlying strata: the Lecho Formation which generally carries minor interstitial copper mineralization, and ultimately from the Pirgua Formation, the probable source of ore-stage metals. An ore-forming low-temperature chloride-rich brine formed in the Pirgua red-beds should be an oxidized fluid capable of transporting the ore metals until they encounter reducing conditions and sulphide in the overlying Yacoraite (and Lecho) formations.
- 6) Textures of some protore iron sulphides suggest that high organic activity was responsible for in-situ reduction of sulphur, with anaerobic bacteria feeding on decaying organic material. This constrains the reduction to syndiagenetic time because the most plausible mechanism for low-temperature reduction of sulphur

from dissolved sulphate or from evaporitic gypsum is bacterial activity, most commonly active in the first few centimetres of organic matter-rich sediments. Nevertheless, isotopic data from pyrite and the ore-stage (Cu-, Pb- and Zn-rich) sulphides indicate that the ore-stage sulphides are distinctly lighter isotopically relative to pyrite, and this observation suggest that some sulphur was introduced to the host rock from a new source. With the limited analyses available, a clear explanation of this source is not possible. A hydrocarbon source is not expected because hydrocarbons were produced after ore-stage mineralization.

As a result of this research, it is also possible to make a few recommendations for additional study to improve the mineralization model for exploration purposes:

- 1) A sedimentologic study at a broader basin-wide scale, in order to provide a more comprehensive sedimentological context for the Juramento mineralization.
- 2) Diagenetic studies (such as cathodoluminescence analyses of carbonates) would help to constrain the interpretations given above. Also, organic-matter maturation studies would provide an independent estimate for the burial history of the host sediments and for the timing of oil/gas generation versus earlier base-metal deposition.
- 3) Sulphide studies (such as broader-scale textural studies to confirm regional-scale metal zoning, and microprobe analyses on sulphide compositions to evaluate the importance of useful and detrimental elements (e.g., Ag and As/Sb in tennantite-tetrahedrite) to orient exploration laterally toward areas of more economic metal concentrations.

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## **Appendix 1**

### **Staining techniques for carbonate thin sections and samples**

The technique used was adapted from Dickson (1965) and Hitzman (1999). This technique used on the Juramento thin sections was found very useful and was applied to most of the samples shown in the figures of this thesis. This technique is recommended at any stage of further field work and core logging because of its great value for rapid identification of carbonates and their textural relationships. A mix of two stains is required (Alizarin Red S and potassium ferricyanide); the following procedure is pertinent for thin sections:

1) Prepare two staining solutions:

Solution **A**: Alizarin Red S - concentration of 0.2 g/100 ml of 1.5% hydrochloric acid.

Solution **B**: Potassium ferricyanide - concentration 2 g/100 ml of 1.5% hydrochloric acid.

- 2) Mix solutions **A** and **B** in the proportions of 3 parts by volume of **A** to 2 parts of **B**.
- 3) Immerse the thin section, or a portion, in the solution for 30 to 45 seconds.
- 4) Wash the stained section in running water for a few seconds.
- 5) Allow to dry.
- 6) Cover with polyurethane varnish or with a cover glass.

For field work and drill core staining purposes, the mixture should be slightly different. The solution should consist of 250 ml of 2% hydrochloric acid to which is added approximately 2 g each of alizarin red S and potassium ferricyanide. The staining solution can be "painted" or applied onto drill core and hand samples. The stained sample or drill core should be rinsed to appreciate the textural relationships between minerals, as is the case for thin sections.

However, several conditions should also be respected, such as the use of plastic or glass containers rather than metal containers for the transport and storage of the solution. Also, the concentration of hydrochloric acid should not exceed 5%, because such a concentration can inhibit the deposition of the stain. In cold weather, avoid the use of extremely hot staining solutions because they can produce cyanide gas. The solution should be kept away from the sun because it degrades. Care must be taken to ensure that the skin and especially the eyes do not come in contact with the solution. Spent staining solution should be disposed of properly.

## **Appendix 2**

### **Sample location list**

|                      |                       |                      |                      |
|----------------------|-----------------------|----------------------|----------------------|
| 1: JDH-1, 74 m.      | 32: JDH-16, 100.8 m.  | 57: JDH-20, 131 m.   | 83: JDH-25, 195.5 m. |
| 2: JDH-1, 83 m.      | 34: JDH-16, 125 m.    | 58: JDH-20, 140.5 m. | 84: JDH-25, 204.3 m. |
| 3: JDH-1, 104.3 m.   | 37: JDH-16, 138 m.    | 59: JDH-21, 51.5 m.  | 85: JDH-25, 204.9 m. |
| 5: JDH-2, 100 m.     | 40: JDH-19, 54 m.     | 62: JDH-22, 102 m.   | 86: JDH-25, 205.2 m. |
| 6: JDH-2, 117. m     | 41: JDH-19, 81.8 m.   | 63: JDH-22, 105.5 m. | 87: JDH-25, 211.6 m. |
| 8: JDH-5, 39 m.      | 42: JDH-19, 97.5 m.   | 67: JDH-25, 57 m.    | 88: JDH-25, 212.6 m. |
| 11: JDH-8, 124 m.    | 43: JDH-19, 100.3 m.  | 68: JDH-25, 66.2 m.  | 89: JDH-25, 94.55 m. |
| 12: JDH-9, 142.8 m.  | 44: JDH-19, 101 m.    | 69: JDH-25, 94.55 m. | 90: JDH-13, 185 m.   |
| 13: JDH-9, 130 m.    | 45: JDH-19, 148.84 m. | 70: JDH-25, 100.6 m. | 91: JDH-25, 210 m.   |
| 14: JDH-12, 81.3 m.  | 46: JDH-19, 150 m.    | 71: JDH-25, 101.5 m. | 92: JDH-25, 79 m.    |
| 17: JDH-12, 100.2 m. | 47: JDH-19, 160 m.    | 72: JDH-25, 103.5 m. | JDH-08-4: 66.5 m.    |
| 20: JDH-13, 178 m.   | 48: JDH-20, 70 m.     | 73: JDH-25, 105.2 m. | JDH-08-5: 71 m.      |
| 21: JDH-13, 178.2 m. | 49: JDH-20, 79 m.     | 74: JDH-25, 118.9 m. | JDH-08-10: 104 m.    |
| 22: JDH-13, 181 m.   | 50: JDH-20, 80 m.     | 75: JDH-25, 121 m.   | JDH-08-11: 104.2 m.  |
| 23: JDH-13, 184.5 m. | 51: JDH-20, 97.8 m.   | 76: JDH-25, 124 m.   | JDH-08-12: 108.25 m. |
| 24: JDH-13, 210 m.   | 52: JDH-20, 98.2 m.   | 78: JDH-25, 138 m.   | JDH-08-14: 111 m.    |
| 25: JDH-13, 217 m.   | 53: JDH-20, 99 m.     | 79: JDH-25, 158 m.   | JDH-08-16: 124.6     |
| 26: JDH-13, 223.3 m. | 54: JDH-20, 100.3 m.  | 80: JDH-25, 161.5 m. | JTH-4: Maria adit    |
| 27: JDH-14, 87 m.    | 55: JDH-20, 106.8 m.  | 81: JDH-25, 169.8 m. | JPS-3: Condor Ridge  |
| 31: JDH-16, 83.4 m.  | 56: JDH-20, 113 m.    | 82: JDH-25, 185.1 m. |                      |