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Journal of Geochemical Exploration 78–79 (2003) 91–97

JOURNAL OF GEOCHEMICAL EXPLORATION

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Abstract

The evolution of fluid flow systems prior to, during, and post MVT mineralization in the Givetian–Frasnian carbonates of the Emanuel Range, Western Australia

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Abstract

The Emanuel Range is part of the extensive Devonian Reef complex, which overlies the Lennard Shelf, a section of shallow basement at the northern end of the Canning Basin in Western Australia. The reef complexes formed in an extensional tectonic environment and host numerous Mississippi Valley-type (MVT) Zn–Pb accumulations. The distribution, relative timing, and origin of calcite, dolomite, and MVT sulphide generations in the southeastern Emanuel Range indicate that the fluid flow systems operating during Middle Devonian to Middle Carboniferous burial changed significantly through time. The topographic flow of meteoric water from north to south, driven through alluvial fans shed from the highlands of the Precambrian Kimberley block to the north of the Emanuel Range, was the longest-lived fluid flow system. The topographic flow system operated intermittently during periods of lowstand in the Givetian and early Frasnian and continued throughout subsequent burial and uplift in the Middle Carboniferous. During early to intermediate burial depths (< 500 m), stratigraphically focused compactionally driven fluids of predominantly modified marine origin entered the reefs from a depocentre to the south of the Emanuel Range. During later burial (1–1.5 km) in the Late Devonian and Early Carboniferous, more deeply sourced fluids were driven laterally into the Emanuel Range from the Fitzroy Trough to the south. The introduction of compactionally driven, hot metalliferous hydrocarbon-bearing brines into the sequence occurred episodically, precipitating MVT sulphides. Between hydrothermal pulses, formation waters decreased in temperature and salinity, due to mixing with cooler surface waters. Hydrothermal brines flowed laterally from south to north until encounter with the Cadjebut Fault, which impeded brine flow. Further brine movement was focused through dilatant faults with a NNE orientation (thought to be related to transfer zones; Vearncombe, J.R., Dentith, M., Doerling, S., Reed, A., Cooper, R., Hart, J., Muhling, P., Windrim, D., Woad, G., 1995. Structural controls on Mississippi Valley-type mineralization, the southeastern Lennard Shelf, Western Australia. In: Sangster, D.E. (Ed.), Carbonate-Hosted Lead–Zinc Deposits. Society of Economic Geologists, Special Publication, vol. 4. 1995, pp. 74–94.) and near-vertical hydraulic fractures related to high fluid pressures. Through time, hydrothermal pulses became both less frequent and less intense, and topographically driven flow again dominated.

Keywords: Lennard Shelf; MVT sulphides; Dolomite; Fluid flow

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1. Introduction

Research into the hydrodynamics of the mineralizing system in the Mississippi Valley-type (MVT)

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0375-6742/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0375-6742(03)00153-5

province of the Lennard Shelf is comparatively in its infancy; however, the lack of alteration of the carbonates and the limited number of basins, which could have potentially contributed fluids to ore accumulations, provide many advantages in elucidating both the number and source of the fluids involved in mineralization. This paper presents the results of a detailed diagenetic study of the southeastern Emanuel Range, an area which hosts three of the six MVT ore accumulations that have been mined to date on the Lennard Shelf.

1.1. Study area

Development of the carbonate succession in the Emanuel Range coincided with a major period of extension, which extended from the Middle Givetian (~ 375 Ma) through to the Early Carboniferous (~ 340 Ma). Extension was centered on the Fitzroy Trough, a northwest/southeast-trending series of half grabens, situated to the south of the Lennard Shelf (Fig. 1) and within 1 km of the southeastern end of the Emanuel Range. Deposition was initiated in the Givetian with the development of evaporitic mudflats (the Cadjebut Formation) on eroded Ordovician sediments. Two major phases of reef development have been differentiated by Playford (1984): (1) a Middle Givetian to Late Frasnian cycle of reef development, referred to as the Pillara Cycle, characterized by the development of back-stepping vertical reef rimmed platforms dominated by stromatoporoids, cyanobacteria, and corals; and (2) a younger Late Frasnian to

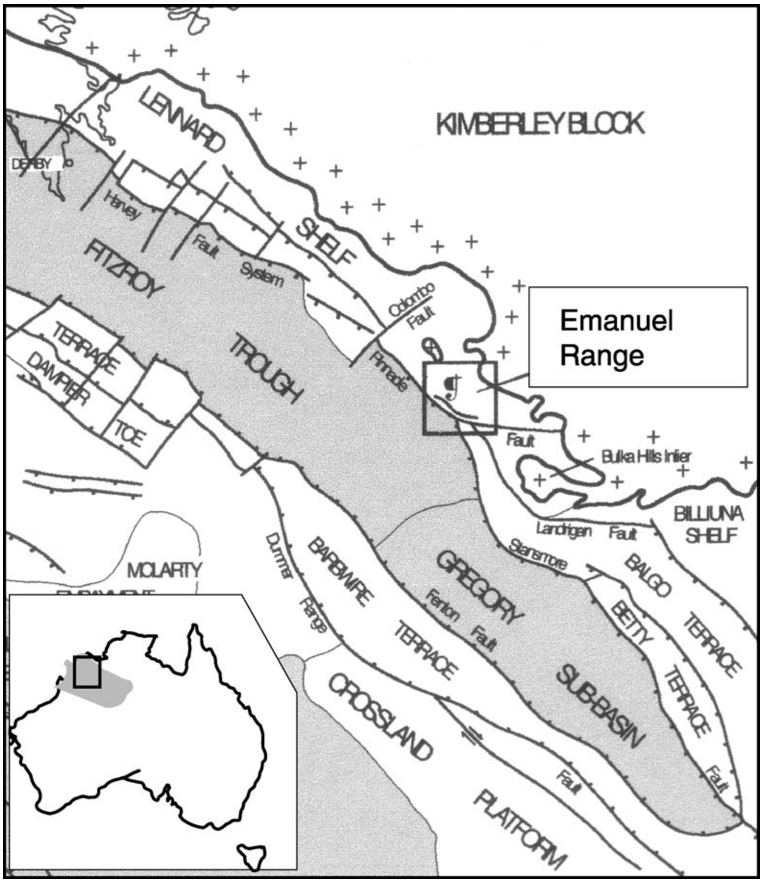

Fig. 1. The locality of the Emanuel Range and the Lennard Shelf.

Famennian cycle of reef development referred to as the Nullara Cycle, characterised by reef margins advancing over their marginal slopes (Fig. 2). Up to 1500 m of Pillara and Nullara Cycle carbonates accreted over the Cadjebut Formation; however, most of the section has been lost to subsequent erosion. The Emanuel Range was exhumed and karsted during the Middle–Late Carboniferous, prior to reburial in the Permian through to the Jurassic. Since the Jurassic, the reefs have been reexhumed, with the current exposure surface roughly coincident with the Carboniferous exposure surface (Arne et al., 1989). MVT mineralization predates Late Carboniferous exposure and has been dated at 350 ± 15 Ma using carbonate cement stratigraphy (McManus and Wallace, 1992) and Rb–Sr dating of sphalerites (Christensen et al., 1995). A strong structural control on the distribution of sulphides is apparent on the Lennard Shelf and all of the MVT accumulations in the Emanuel Range either occurring next to, or within, major faults and fractures.

1.2. Methods

Samples from all stages of reef development were examined in plain light microscopy and under cathodoluminescence and ultraviolet excitation to establish the cement stratigraphy and distribution of cementing phases. Geochemical and fluid inclusion analyses were conducted on selected samples from Middle Devonian to Middle Carboniferous burial, focusing on phases associated with mineralization in two MVT deposits (Goongewa and Cadjebut East), in an effort to establish the fluids present from sedimentation up to Late Carboniferous exposure. All in excess of 90 wells were logged in the Emanuel Range (>70 in the SE Emanuel Range) to establish the distribution of dolomite and mineralization. Four distinct dolomite generations occur within the Emanuel Range, which have been previously referred to in the literature as dolomites I–IV (DI–DIV) (Tompkins et al., 1994). The nomenclature is retained here to avoid confusion. DI is nonferroan to weakly ferroan and finely crystalline. It is confined to the evaporitic Cadjebut Formation and is thought to have formed during synsedimentary brine reflux (Pedone, 1990). Cadjebut Formation was not examined in this study, which focused on the overlying subtidal units of the Pillara Cycle; hence, the diagenetic sequence discussed does not include DI.

2. Results

2.1. Paragenesis

The earliest cements to postdate marine cements in the subtidal Pillara limestones overlying the evaporitic

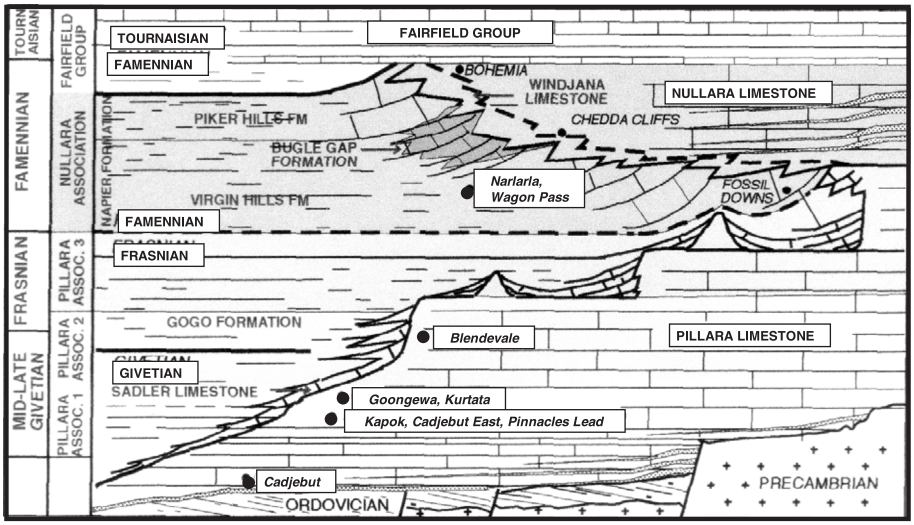

Fig. 2. Stratigraphy of the Devonian section of the Lennard Shelf after Playford (1984).

Cadjebut Formation in the Emanuel Range are nonferroan nonluminescent to very dully luminescent (VDL) equant calcite cements (Fig. 3), which have been shown by geochemical modeling to have formed during shallow burial from waters of mixed marine–meteoric parentage (Pedone, 1990). In nonmineralized samples, VDL calcite cements are postdated sequentially by: (1) red luminescent, weakly ferroan medium crystalline replacement dolomite and cements (DII); (2) moderately dully luminescent, ferroan calcite cements (MDL); (3) nonluminescent, strongly ferroan, medium to coarsely crystalline replacement dolomite and cements, with brightly luminescent rims (DIII); (4) dully luminescent weakly ferroan calcite (DLC); and (5) late brightly banded luminescent calcite cements (LBL) (Fig. 3).

In mineralized samples, base metal sulphides postdate the nonluminescent cores of DIII cements, and exhibit complicated intergrowth relationships with the younger brightly luminescent generations of DIII. In addition, even though the Emanuel Range is undermature for oil generation (Wallace et al., 2002), oil inclusions occur within growth zones in the rims of DIII cements, indicating that oil migration coincided with base metal sulphide precipitation. Red luminescent coarsely crystalline ferroan dolomite (DIV) is present in some samples and both predates and postdates base metal sulphides. Some crystals of DIV cement exhibit lattice curvature; however, more commonly, they are planar. Poikilotopic DLC generally occludes free cavity space remaining after sulphides. The occurrence of DIII, DIV, and sulphides along high-amplitude stylolites in otherwise undolomitised samples indicates that these phases must have postdated significant pressure solution.

Cadjebut East and Goongewa deposits both occur within the hanging wall of the Cadjebut Fault; however, whereas sulphides are largely hosted within fractures and dissolution cavities in undolomitised reef-flat limestone at Cadjebut East, they are predom-

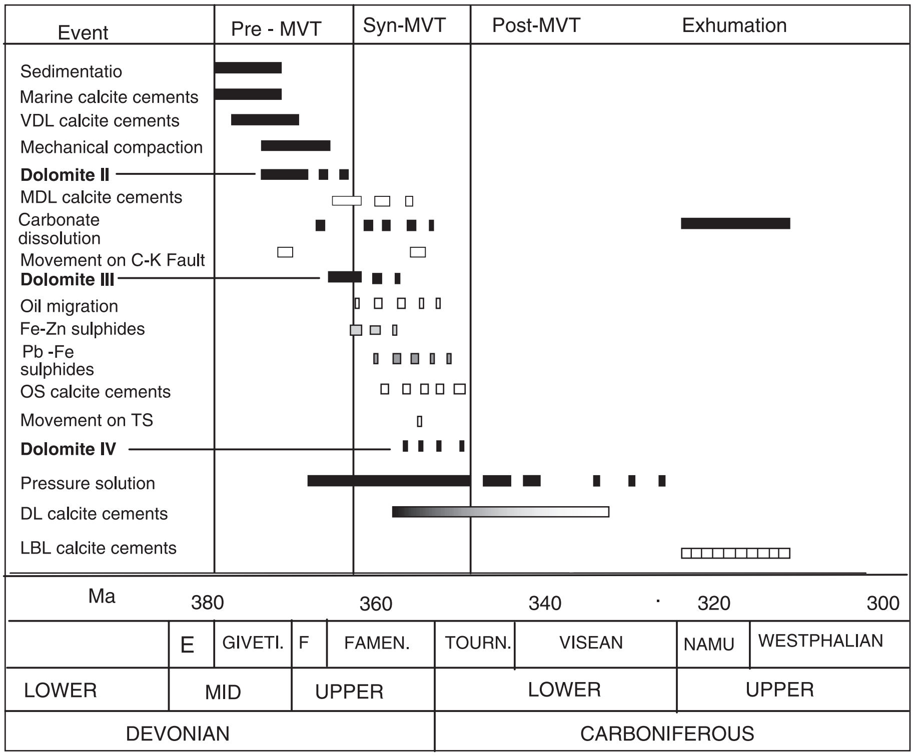

Fig. 3. Generalised paragenetic sequence for the Emanuel Range.

inantly hosted within secondary fracture porosity and vugy dissolution porosity in dolomitised (DIII) reef-flat and back-reef subfacies at Goongewa. An expanded paragenetic sequence is observed within the ore deposits, with at least four major cycles of sulphide mineralization present. Three complete cycles of mineralization, comprising sphalerite, postdated by sphalerite plus galena, followed by maracasite and finally ore-stage calcite (OSC) occur at Goongewa, while only two complete cycles of mineralization occur at Cadjebut East. At both deposits, main-stage mineralization is postdated by several generations of marcasite alternating with OSC; however, at Cadjebut East, late-stage galena-rich fracture filling mineralization is also present.

2.2. Microthermometry

The fluid inclusion assemblage (FIA) within ore-stage calcites (OSC) at both Goongewa and Cadjebut East comprises single-phase aqueous inclusions and two-phase aqueous–vapour inclusions. Homogenisation temperatures vary from 50 to 90 °C, with modal temperatures of 65 °C recorded for three different generations of OSC at Goongewa and two different generations at Cadjebut East. Cross-plots of inclusion size vs. homogenization temperature indicate that the inclusions in all OSC are stretched, suggesting that actual precipitation temperatures were probably even lower. Last melt temperatures for OSC are highly variable, ranging between -0.1 and -20.1 °C, indicating the presence of fresh waters (0.3% $NaCl_{(equiv)}$) to highly saline brines with salinities of up to 23% $NaCl_{(equiv)}$. The FIA within DIII cements and sphalerite generations consists predominantly of two-phase aqueous–vapour inclusions, with rare single-phase liquid-only inclusions also present. Homogenization and last melt temperatures for inclusions indicate that the parent fluids were both more uniformly saline (15–25 wt.% $NaCl_{(equiv)}$) and warmer than the fluids from which OSC precipitated. Homogenisation temperatures vary between 59 and 106 °C for DIII (mode ~ 80 °C), between 50 and 82 °C (mode ~ 70 °C) for S2, and between 77 and 89 °C (mode ~ 82 °C) for S3. Cross-plots of inclusion size vs. temperature indicate that inclusions in DIII and sphalerite are unstretched and likely to reflect temperatures of the brines during precipitation. Rare primary fluid inclusions found within DLC cements record homogenization temperatures of between 50 and 78 °C, and have salinities varying between brines and fresh waters (< 1% to 10% $NaCl_{(equiv)}$).

2.3. Stable isotopes

$\delta^{18}O$ and $\delta^{13}C$ values for the ore-stage calcites are variable, with $\delta^{18}O$ values ranging between -5.5‰ and -12.5‰ PDB and $\delta^{13}C$ between $+0.5$‰ and -4.2‰ PDB. Assuming precipitation temperatures of between 50 and 70 °C, then OSC cements at Goongewa appear to have formed from fluids with ^{18}O compositions of between -4 and $+4$ SMOW, while those at Cadjebut East, which have less depleted and less variable $\delta^{18}O$ values, formed from a fluid(s) between $+2$ and $+4$ SMOW. $\delta^{18}O$ and $\delta^{13}C$ values for DII range between -1.1‰ and -6.1‰ PDB and between $+0.7$‰ and 2.9‰ PDB, respectively, while values for DIII are generally more depleted, with $\delta^{18}O$ values ranging between -4.6‰ and -6.9‰ PDB and $\delta^{13}C$ values varying between -0.1‰ and 2.8‰ PDB. Limited data obtained for DIV cements indicate that the parent fluids of DIII were probably more enriched in ^{18}O than DII (4.2‰ and -5.2‰ PDB, $n=5$) while $\delta^{13}C$ values are similar to earlier dolomite generations (0.5–2.3‰ PDB).

2.4. Spatial distribution of dolomite

DII is restricted to the basal Pillara limestone (the Argutastrea Unit; Pedone, 1990), decreasing in thickness from the Pinnacles Fault to the south, where it reaches a thickness of about 30 m, to the north, where it decreases to < 5 m in thickness. The uniform thickness of DII across the Cadjebut and Kapok Faults indicates that it predates fault movement (Fig. 4A). The basal 300 m of Pillara limestone from the Pinnacles Fault (the major bounding fault of the Fitzroy Trough) north to the Cadjebut Fault are pervasively dolomitised by DIII; however, north of the Cadjebut Fault, DIII is only present directly adjacent to the Cadjebut Fault, indicating that DIII postdated significant movement on the Cadjebut–Kapok Fault (Fig. 4B). DIV occurs ubiquitously with mineralization (generally late-stage galena-rich mineralization) and is the only dolomite generation present within mineralized vertical fractures and

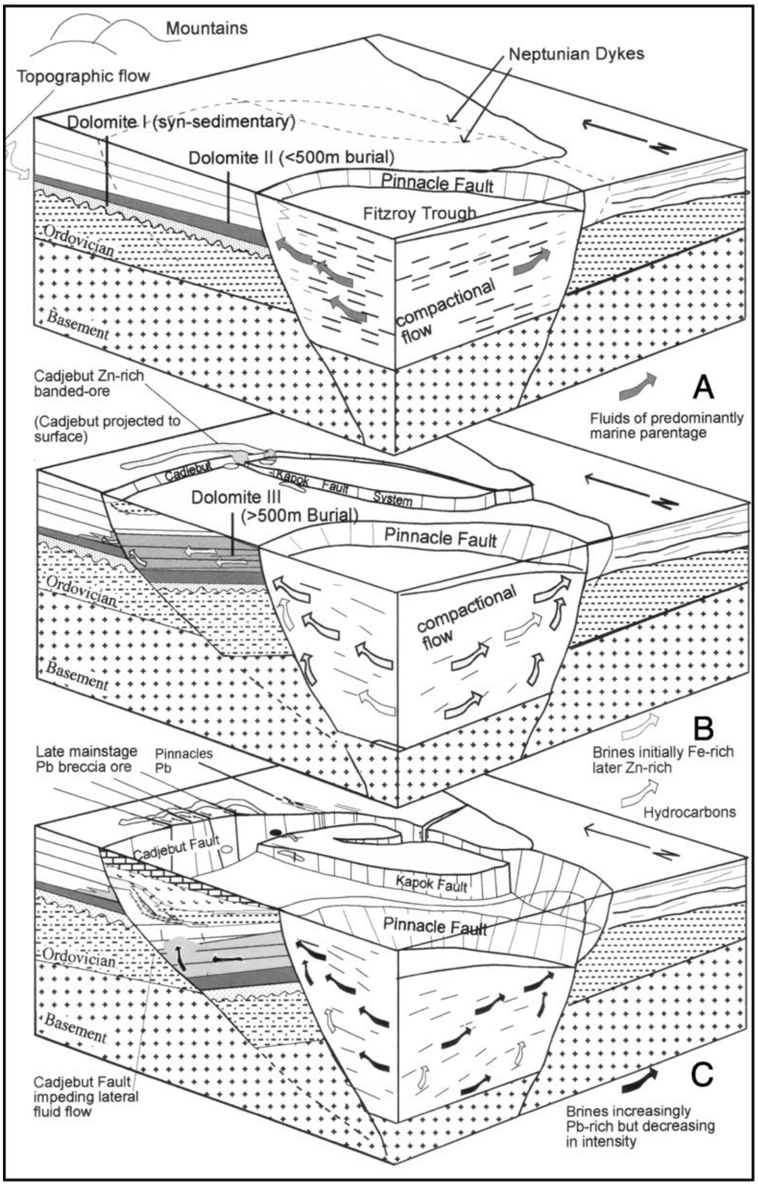

Fig. 4. The structural evolution of the southeastern Emanuel Range.

minor N–S striking faults present in the Emanuel Range (Fig. 4C).

3. Discussion and conclusions

Stratigraphic thickening across the Cadjebut Fault indicates that the fault had begun to move by the time the basal Pillara limestone had reached 500 m; therefore, DII, which predates fault movement, must have formed at intermediate burial depths of <500 m. At burial depths of <500 m, the geochemistry and geometry of DII are consistent with formation from (<60 °C) compactional waters of predominantly marine origin directed laterally into the platform from the depocentre to the south and moving laterally northwards (Fig. 4A).

The geometry of DIII indicates that it postdated significant movement on the Cadjebut Fault. The dolomitising fluids were hot (80–110 °C), highly saline brines, which traveled laterally from south to north confined beneath the overlying Gogo Shale. The brines pooled to the south of the Cadjebut Fault against the Emanuel Shale in the footwall of the fault (Fig. 4B), with movement restricted to ascension through near-vertical fault and fracture systems.

The alternation of hot, more uniformly saline fluids (precipitating DIII, DIV, and MVT sulphides) with cooler fluids (precipitating OSC) is consistent with highly saline brines being episodically released from a deeper depocentre to the south of the Emanuel Range. Between brine pulses, the cooler, less saline formation waters mixed with the brines precipitating OSC.

The geochemistry and fluid inclusion data for DLC are consistent with their formation from a mixture of brines and meteoric water with a greater contribution of meteoric water during later formed DLC. They are interpreted to have formed predominantly during burial from solutes released from the pressure solution of the host limestones in a fluid system that became increasingly dominated by meteoric water with time.

Tompkins et al. (1997) recorded lower homogenization temperatures and salinities in late-stage OSC than in sphalerite at Cadjebut Mine and interpreted this as indicating that the mineralizing fluids had become less saline through time. Consequently, Tompkins et al. (1997) concluded that mineralization occurred in the Middle Carboniferous just prior to exhumation. In contrast, we interpret the data from the current study to indicate that mineralization occurred during active burial of the reefs, with hot brines episodically introduced into a low-salinity and low-temperature system that was dominated by a topographic fluid flow regime.

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