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Hydrothermal dolomite distribution in the Emanuel Range as a constraint on timing of fault movement during mineralisation on the Lennard Shelf, Western Australia

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SUMMARY

At least four petrographically, geochemically, temporally and spatially distinct dolomites have been identified in mid-late Devonian carbonate banks and reefal buildups of the Emanuel Range on the south eastern Lennard Shelf. Detailed mapping of the distinct dolomite bodies and their relationship to extensional faults and MVT-sulphide mineralisation has allowed the structural evolution of the southeastern Emanuel Range to be reconstructed providing constraints on the structural evolution of the range during oil migration and MVT mineralisation.

The earliest dolomite (DI) is a stratigraphically-controlled, finely crystalline, non-ferroan, fabric mimetic syndepositional dolomite that is associated with evaporitic mudflats and predates major fault movement. Dolomite II (DII) is also stratigraphically controlled and is restricted to the basal section of the Argutastrea Unit which overlies the Lower Dolomite Unit. DII comprises fine to medium crystalline weakly ferroan replacement dolomite and cements which formed during early burial (<500 m) when primary porosity was relatively high.

Following extension-related major movement on the Cadjebut Fault during the Mid to Late Devonian, hot 60-106 °C highly saline basinal brines entered the reefs precipitating a medium to coarsely crystalline, variably ferroan Dolomite III (DIII). DIII distribution indicates that brines utilised the Pinnacles and Cadjebut Splay Faults rather than the Cadjebut Fault. The onset of oil migration coincided with the later stages of DIII formation and the onset of MVT-sulphide mineralisation. Leaching of bioclasts associated with DII and DIII resulted in the development of variably abundant secondary mouldic and vuggy porosity which in some cases is maintained in the subsurface forming potential reservoir facies.

The final generation of dolomite is coarsely crystalline, variably ferroan Dolomite (DIV), which can exhibit pronounced lattice curvature and is associated with MVT sulphides. Both Dolomites DIII and DIV are hydrothermal dolomites (HTD) having formed at temperatures up to 30°C higher than maximum burial temperatures of the host sediments.

Key words: dolomite, hydrothermal dolomite (HTD), Zn-Pb deposit, Mississippi Valley-type, Lennard Shelf.

INTRODUCTION

Understanding the origin of dolomites is of interest to mining and petroleum industries as they form the best reservoirs in carbonate systems and may form major aquifers in the subsurface due to their enhanced permeability. However even though the most productive oil reserves on the Lennard Shelf, occur within fractured dolomites, as do many of the MVT deposits, the dolomites of the Lennard Shelf have been the focus of few detailed studies.

The first systematic study of the complexity of dolomitisation in the Emanuel Range is that of Pedone (1990), who identified four petrographically, geochemically and spatially distinct dolomites within the basal Pillara sequence. These dolomites have been referred to by Tompkins et al. (1994a) and Middleton and Wallace (2003) as Dolomites I-IV (DI-DIV) and the nomenclature is retained here to avoid confusion.

The Emanuel Range was selected for study as it is the most extensively dolomitised range cropping out on the Lennard Shelf and has been extensively drilled for sulphides providing good three-dimensional coverage of the area. The atoll is situated adjacent to the Pinnacle Fault, a major bounding fault of the Fitzroy Trough that was a major source of hydrothermal fluids to the Lennard Shelf during and after Pb-Zn mineralisation and which hosts four of the six ore-bodies mined on the Lennard Shelf to date.

GEOLOGICAL SETTING

The Emanuel Range (Figure 1) is part of an 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 southern limit of the Lennard Shelf is defined by the Beagle Bay-Pinnacle Fault Complex, which began movement in the Middle Devonian and has a maximum displacement of at least 6 km (Vearncombe et al., 1995).

Two major phases of reef development have been differentiated by Playford (1980) for the reefs on the Lennard Shelf: (1) A mid-Givetian to late Frasnian cycle of reef development, referred to as the Pillara Cycle, characterised by the development of back-stepping vertical reef rimmed platforms dominated by stromatoporoids, cyanobacteria and corals; and (2) A younger late Frasnian to Famennian cycle of reef development referred to as the Nullara cycle characterised by reef margins advancing over their marginal slopes. Sequence stratigraphic studies interpret the Pillara and Nullara Cycles of reef development as forming a transgressive-regressive cycle on which higher order fluctuations in sea-

level are imposed (Kennard et al., 1992; Southgate et al., 1993).

Copp (2000) differentiates the Pillara and Nullara Cycles of reef development into a number of associations based on changes in the style of platform growth, recognising three distinct associations in the Pillara Cycle of reef development and one in the Nullara Cycle. Except for Famennian Nullara stage limestones preserved in the hanging wall of the Cadjebut Fault, carbonates of the Emanuel Range are largely restricted to the lower two associations of the Pillara Cycle (Figure 2).

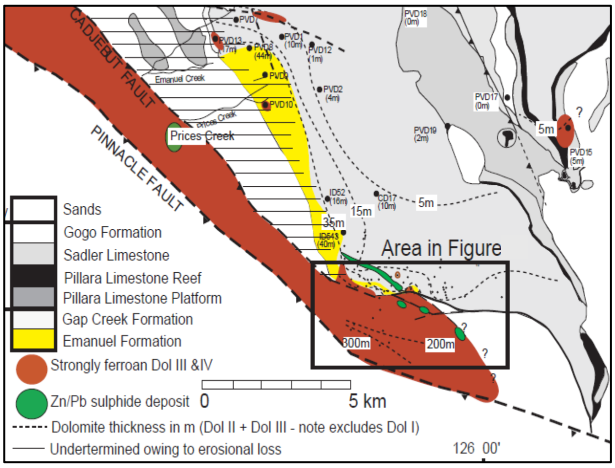

Figure 1. The Emanuel Range illustrating distribution of dolomite types. Thickness of DII is contoured. Distribution of DIII + DIV is indicated in brown.

Development of the carbonate succession in the Emanuel Range coincided with a major period of extension, (the Pillara Extensional Movement, of Shaw et al., 1994) which extended from the middle Givetian (~375 Ma) through to the Early Carboniferous (~340 Ma), centred on the Fitzroy Trough, a north west/south east trending series of half grabens, situated to the south of the Lennard Shelf. Over 1100 m of carbonates from the Pillara and Nullara Cycle are estimated to have accreted over the Cadjebut Formation, however most of the section has been lost to subsequent erosion, with Nullara Cycle sediments now only preserved in the hanging wall of the Cadjebut Fault.

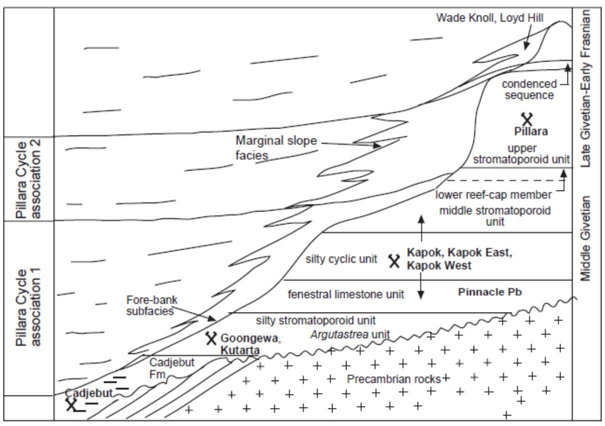

Figure 2. Pillara Associations 1 and 2 from Copp (2000) indicating stratigraphic location of ore deposits and BHPs stratigraphy for the SE Lennard Shelf.

The southern side of the Emanuel Range is downthrown into the Pinnacle Fault, one of the major bounding faults of the Fitzroy Trough (Figure 1) delineating the southern margin of the Lennard Shelf. The base of the Devonian succession is displaced by 3 to 5 km by the Pinnacle Fault (Dörling, 1995) along the southern end of the Emanuel Range, although the total vertical displacement on the fault is up to 15 km (Drummond et al., 1991). From seismic profiling the Pinnacle Fault appears to detach at depth into the evaporitic rocks of the Ordovician to Silurian Caribuddy Group (Drummond et al., 1991).

The Cadjebut Fault is a major normal fault which branches from the Pinnacle Fault and has down thrown the southern Emanuel Range by about 750 m, although the extent of throw varies along the length of the fault. The Kapok Fault branches from the Cadjebut Fault and delineates the southern end of a downthrown block which has detached from the Cadjebut Fault. All known major MVT accumulations in the Emanuel Range occur either within, or adjacent to the Cadjebut and Kapok Faults. This close spatial relationship between major ore accumulations and major structures occurs throughout the Lennard Shelf (Dörling et al., 1996).

METHODS

Core from 90 wells drilled in the Emanuel Range were stained using alizarin-red and potassium ferricyanide, and logged for the presence of ferroan and non-ferroan dolomite from the top of the Cadjebut Formation through to the top of the Devonian sequence (Figure 3). The individual cores to be examined were selected to establish the spatial distribution of dolomites in the Emanuel Range, and the relationship of the dolomite types to the major faults and to sulphide mineralisation. The extent of dolomitisation was also mapped at surface to confirm relationships established in core.

DI is confined to the evaporitic Cadjebut Formation and is thought to have formed during synsedimentary brine reflux (Pedone, 1990). The Cadjebut Formation is not examined in this study, however its distribution is evident in later cross sections where it is illustrated as the Lower Dolomite Unit (LDU).

The weakly ferroan fine-medium crystalline dolomite (Dolomite II), and the strongly ferroan medium to coarsely crystalline dolomite (Dolomite III), are the two most volumetrically important post syn-sedimentary dolomites in the Emanuel Range. Dolomite II weathers to a buff colour in the field and Dolomites III and IV to a deep red-brown as a consequence of their higher iron content. The difference in colour on weathering allows strongly and weakly ferroan dolomites to be easily distinguished in the field making mapping of dolomite distribution a straightforward procedure. In core, matrix dolomites are grey, and cements generally light pink for all dolomites and distinction between the types requires staining with potassium ferricyanide. Distinction of the medium to coarsely crystalline, strongly ferroan Dolomites III and IV requires petrographic study.

Two hundred and thirty thin sections were examined from selected cores for dolomite types and paragenetic relationships between calcite cements, dolomites and sulphides. Thin sections were stained with alizarin-red and potassium ferricyanide and examined using both conventional petrography and cathodoluminescence using a Nuclide cold cathode luminoscope™ (model ELM-2B), with a 9 kV DC beam energy, a beam current of 0.6 to 0.8 mA DC and a spot diameter of ~1 cm. Ultraviolet fluorescence microscopy was

performed on a Nikon fluoroscope using violet and ultraviolet wavelengths. Fluid inclusion analysis was conducted on a Fluid Inc adapted U.S.G.S. gas flow heating/freezing stage, calibrated with Fluid Inc standard inclusion mounts (mounted on a Zeiss Universal microscope with a Nikon long working distance 40X objective). Microthermometry measurements were cycled with precision of recorded temperatures of first ice melting (eutectic temperatures, (T_e) and temperatures of final ice melting ($T_{m_{ice}}$) ± 0.5°C and (T_h) ± 1.0°C.

PARAGENESIS

Primary porosity within the subtidal Pillara platformal limestones is restricted to grainstones, internal cavities in bioclasts (predominantly gastropods), fenestrae (which range from several mm to several centimetres in size), and small intra-skeletal pores in stromatoporoids (which range from several microns to several tens of microns in size).

The distribution of DII is restricted to the base of the Argutastrea Unit (Figure 2), which overlies the evaporitic Lower Dolomite Unit (LDU).

The first cements to overlie micritic and scalenohedral marine cements in the Argutastrea Unit are Very Dully Banded Calcites (VDBC or EBC1 of Pedone, 1990). These are post-dated by Moderately Brightly Luminescent cements (MBLC or EBC2 of Pedone, 1990). The VDBC cements are very early, however geochemical modelling indicates they are formed from mixed marine meteoric water (Pedone, 1990). DII cements show complicated intergrowth relationships with the later stages of VDBC.

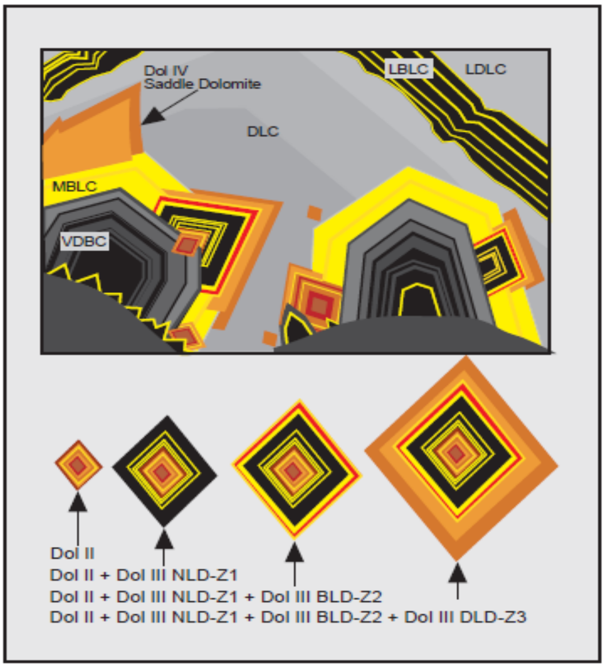

Figure 3. Paragenesis of Argutastrea Unit, marine cements are overgrown by VDL calcite cements. DII shows complicated intergrowth relationships with the later stages of VDL calcite. Zoned DIII cements overgrow VDBC and DII cements and show intergrowth relationships with MBLC.

In pervasively dolomitised lithologies, replacement DII appears as subhedral to anhedral mosaics of crystals of 10 to 150 µm (average=30-80µm) across. The presence of numerous small (typically <1µm) inclusions gives the crystals a cloudy appearance. In partially dolomitised lithologies, isolated rhombs of euhedral dolomite occur in association with other crystal morphologies. Under crossed polars both euhedral and subhedral dolomite crystals exhibit straight extinction. Under cathodoluminescence, the inclusion-rich cores of DII rhombs are uniformly red-luminescent to dully banded if well preserved (Figure 3). Locally however, the centres of the dolomite crystals exhibit patchy bright luminescence, indicating alteration.

DIII is highly ferroan (concentrations of 30,000 to 50,000 ppm Fe were detected for early DIII using electron microprobe) and crosses formation boundaries. Its presence is restricted to the southern area of the Emanuel Range near the Cadjebut Fault and along other structures linked to the Cadjebut Fault such as the Kunian Fault. In pervasively dolomitised intervals, crystals of replacement DIII form mosaics of subhedral (planar-s) to anhedral (planar-a) crystals with individual rhombs ranging from 20 to 450 µm across (x=80-250 µm). In partially dolomitised lithologies, isolated rhombs of euhedral DIII occur in association with other crystal morphologies. When the crystals have a euhedral morphology they commonly exhibit cloudy cores and limpid rims. Under crossed polars the euhedral dolomite crystals exhibit straight extinction and anhedral crystals exhibit weak undulatory extinction.

Under cathodoluminescence the cores of DIII are non-luminescent (Non-luminescent Dolomite Zone 1 NLD-Z1) and the rims exhibit brightly banded luminescence which can be separated into early Bright Luminescing Zones (BLD-Z2) and later Dully Luminescing Zones (DLD-Z3) (Figures 3 and 4).

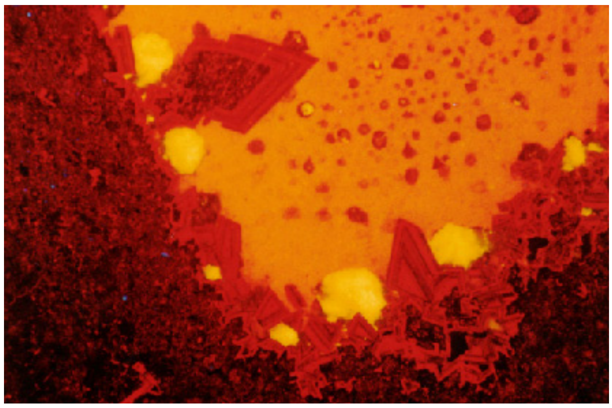

Figure 4. Sphalerite (brightly luminescent spheroids) overgrowing DIII (DLD Z3) pore is occluded by ore-stage calcite which has the same timing as MBLC.

Sulphide mineralisation postdates the early stages of DIII and exhibits similar timing to the precipitation of DLD-Z3 which forms the outer rims of DIII.

Red luminescent, variably ferroan DIV has a similar distribution to DIII but in addition is found in near vertical fractures away from DIII. DIV is often associated with sulphide mineralisation and frequently completely recrystallises earlier dolomite generations. Because of the similar timing and the fact that it is indistinguishable from the outer zones of DIII, DIV is very probably simply an extension of DIII. However, because it has a different distribution to DIII and at times exhibits the pronounced lattice curvature of

saddle dolomite, it is considered a separate phase here (Figure 3).

Although uncommon, oil inclusions are sometimes present in the later stages of DIII and in DIV indicating hydrocarbon migration coincided with this period of dolomitisation (Figure 5) Middleton and Wallace (2003).

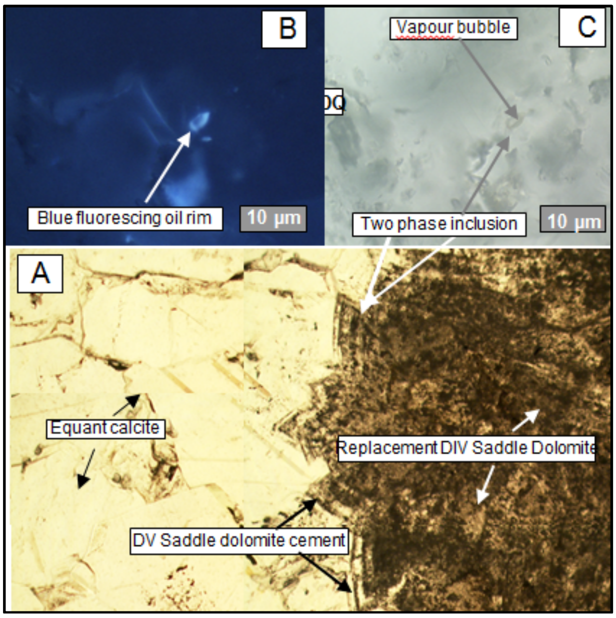

Figure 5. Oil inclusion in rim of DIV Saddle dolomite.

MICROTHERMOMETRY

The Fluid Inclusion Assemblage (FIA) within DII dolomite cements consists predominantly of single-phase liquid-only inclusions with rare two phase aqueous – vapour inclusions. A single T_h result obtained for the rim of a DII rhomb recorded a temperature of 58°C. The FIA within DIII dolomite cements consists of two-phase aqueous – vapour inclusions with rarer liquid-only inclusions. Microthermometry on DIII cements indicates formation from highly saline fluids (15-25 wt% $NaCl_{equiv}$) at temperatures of between 55 and 106°C (mode ≈75°C) Figure 6.

Ore-stage calcites in the Emanuel Range record T_h values with reproducible modal temperatures of ≈65°C which are estimated to be close to the host rock burial temperature at the time of mineralisation (Wallace et al., 2001). Cross-plots of inclusion size T_h in ore-stage calcite inclusions indicate that these inclusions formed at lower temperatures and have been stretched during later burial Wallace et al. (2002).

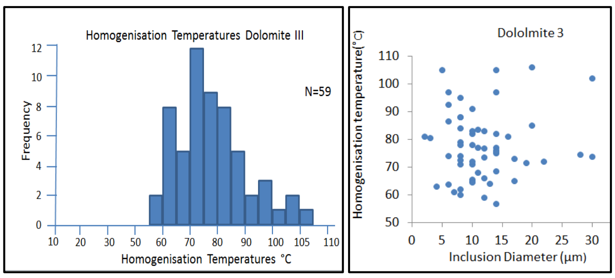

Figure 6. Homogenisation temperatures in DIII (left) and cross-plot of inclusion size versus temperature (right).

DIII, which predates mineralisation in the Emanuel Range, record T_h modal temperatures of ≈75°C, at least 10 °C hotter than the temperature of the host rocks at the time of dolomitisation and so are hydrothermal dolomites by the definition of Davis and Smith (2006). Unlike the ore stage calcites reported by Wallace et al. (2001) cross plots of inclusion diameter versus homogenisation temperatures for dolomite and sulphides exhibit no obvious stretching trends (Figure 6). This is possibly in part because the inclusions within dolomite and sphalerite are in slightly more robust minerals but also is likely to be because the inclusions are a lot smaller in the dolomites and the sphalerites than they are in ore-stage calcites and smaller inclusions are less susceptible to stretching.

DISTRIBUTION OF DOLOMITE

DII is restricted to the basal Pillara Limestone (the Argutastrea Unit, Pedone 1990). It is the most aerially extensive dolomite and thins from the Cadjebut Fault where it is around 20 m thick (dark grey Figure 7) to less than 5m further north in the Emanuel Range (contours on grey in Figures 1 and Figure 7).

The uniform thickness of DII across the Cadjebut and Kapok Faults indicates that it predates fault movement (Figure 8).

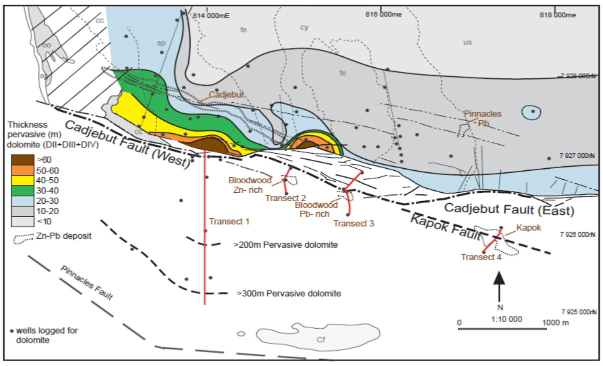

Figure 7. Southern area of the Emanuel Range outlined in Figure 2 showing the distribution of dolomite types. DII (grey) is approximately 20 m thick (dark grey) near the Cadjebut Fault and thins to less than 10 m thick to the north (light grey). DIII is > 300 m thick north of the Pinnacles Fault, thinning to 60 m thick near two jogs on the Cadjebut Fault where it rapidly drops off to < 40 m thick (green) then <30 m thick (pale blue). Note coloured zones represent combinations of DII, DIII and DIV in this figure.

Highly ferroan dolomite DIII pervasively dolomitises the basal 200 to 300 m of the Pillara Limestone north of the Pinnacles Fault. However, even though it is present along the Cadjebut Fault it is not very intense to the north of the Fault (Figure 7) where it appears to enter the platform at two points (potentially dilational jogs) indicating emplacement of DIII must postdate significant movement on the Cadjebut Fault. However major movement on the Cadjebut Fault also postdates emplacement of DIII as is evident in Figure 8. The final phase of dolomitisation DIV is the only phase observed in near vertical fractures associated with Pinnacles Pb and other fracture-hosted mineralisation, and is related to high fluid pressures in the latter stage of mineralisation (Stage 3 of Figure 3).

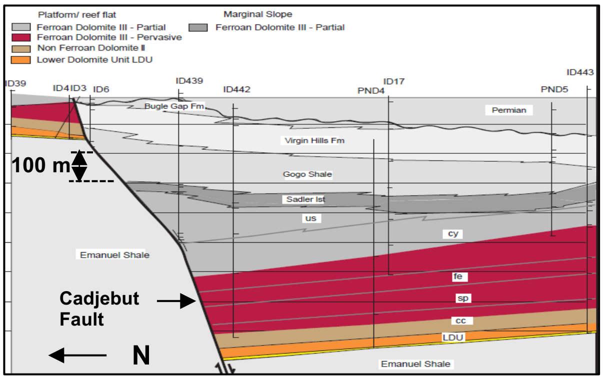

Figure 8. Transect 1 in Figure 7, cross section across Cadjebut Fault. ID443 is furthest south. Lower Dolomite Unit (LDU in orange is DI), cc beige is DII, DIII is red-brown, impacting Silty Stromatoporoid Unit (sp) and fenestral limestone (fe).

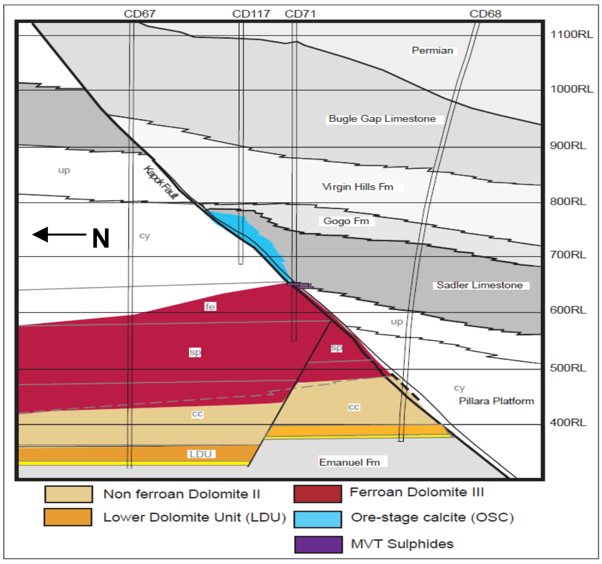

Figure 9. Transect 4 in Figure 7, illustrating major movement on the Kapok Fault following emplacement of DIII.

CONCLUSIONS

Study of the dolomites in the Emanuel Range has enabled the structural development of the Emanuel Range to be determined placing constraints on fault movement at the time of sulphide emplacement. DII was formed prior to fault movement from compactional fluids of mixed marine origin, DIII and DIV were emplaced during active subsidence from basinal brines formed at higher temperatures than the host rocks; hence these are hydrothermal dolomites. Although relatively warm, brine temperatures of 75-80°C are permissive of Bacterial Sulphate Reduction BSR occurring (Machel, 2001) during MVT mineralisation.

Even though DIII and mineralisation fluids were at least 10-15°C hotter than the host rocks they invaded no geothermal anomaly is evident (Arne, 1996), which is consistent with mineralisation occurring prior to full burial or from hot, short-lived pulses of fluid that did not thermally alter the surrounding host rock.

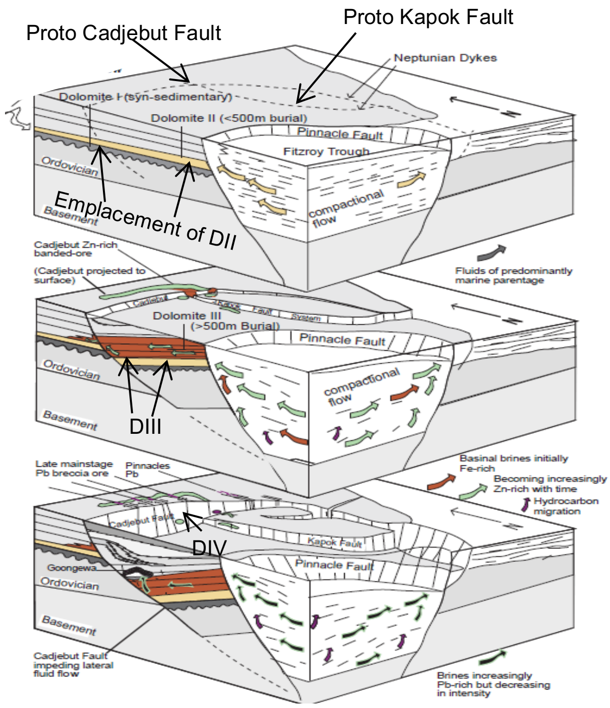

Figure 10. Structural evolution of south eastern Emanuel Range relative to dolomite emplacement.

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