# Litho-structural controls on mineralisation at the Pillara carbonate-hosted Zn-Pb Deposit, Lennard Shelf District, Western Australia

**Dennis Arne***
*Telemark Geosciences Pty Ltd*
*Yackandandah, VIC*
*dennis.arne@telemarkgeosciences.com*

**Simon Dörling**
*Rock Domain Consulting*
*Perth, WA*
*sdorling@rockdomain.com.au*

**Robert Fagan**
*Curtin University*
*Kalgoorlie, WA*
*robertfagan345@gmail.com*

**Heather Middleton**
*NRAR DPI*
*Parramatta, NSW*
*Heather.Middleton@damsafety.nsw.gov.au*

## SUMMARY

The Pillara Zn-Pb deposit is located on the northeast margin of the Canning Basin, Western Australia where it is hosted by a series north-northeast-trending, en echelon, conjugate normal faults that bound a central graben plunging gently to the northeast. Kinematic indicators on all fault surfaces indicate dominantly dip-slip movement. Extension increases from approximately 15% in the south to as much as 50% in the north of the graben structure. The complex array of faults is consistent with development in a northwest-southeast directed extensional stress field with a vertical $\sigma_1$ prior to minor tilting of the sequence to the northeast. Northwest-southeast extension was localised within a northeast-trending transfer structure.

Local controls on the development of mineralisation plunging shallowly to the northeast include dilation where faults steepen or overlap and where antithetic faults intersect the main bounding Western and Eastern Faults. Areas of greatest dilation are largely controlled by the orientation of individual fault segments relative to the local stress field and the intersection of the faults with a competent fenestral limestone unit (Unit 5) and lower platform and bank facies (Unit 1). Both units display low uniaxial compressive strengths compared to other limestone samples within the sequence. The intersection of north and northeast trending fault segments defines a steep, northerly plunge that appears to control high grade orebodies in the F10 system (A Lode and B Lode).

Mineralisation is dominantly contained within tectonic breccia zones, open-space fill along faults, and extensive hanging-wall hydraulic breccia zones localised by fault relays and intersections with antithetic faults. The latter grade outwards from rubble-breccia through mosaic breccia to crackle breccia and stockwork vein zones. Veins and breccias may show a history from early marine calcite cements through to pre-ore marcasite and calcite-cemented crackle breccia ($B_0$), to ore-stage breccias characterised by sulphide-cemented rubble breccias ($OB_1$) at times incorporating sulphide breccia clasts ($OB_2$), to post-ore breccias cemented by sparry calcite cement ($OB_3$). The ore textures and paragenetic sequence are consistent with introduction of the ore fluids during active fault movement, and rapid precipitation into open cavities created during faulting.

**Key words:** Pillara Zn-Pb deposit, Mississippi Valley-type, Lennard Shelf.

## INTRODUCTION

The Pillara Zn-Pb deposit, formerly known as Blendevale, is the largest single deposit of the Lennard Shelf carbonate-hosted Zn-Pb (Mississippi Valley-type, or MVT) district in Western Australia, with a historical resource of 20 Mt @ 8 % Zn, 2.5 % Pb and 17 g/t Ag (Murphy, 1990). The Pillara deposit, along with Kapok (Figure 1), is clearly structurally controlled, although other deposits on the Lennard Shelf, such as Cadjebut, Goongewa and Kutarta are also located close to major faults (Vearncombe et al., 1996).

Although structural controls on mineralisation have been implicated for MVT districts elsewhere, these controls are often poorly documented or inferred. The Pillara deposit represents a unique opportunity to describe structural controls on MVT mineralisation through access to several hundred kilometres of diamond drill core and, more significantly, underground access between 1997 and 2003. Previous descriptions of the Pillara deposit (Murphy et al., 1986, Vearncombe et al., 1995) relied on diamond drill core only.

The current study presents a compilation of observations made by Western Metals Ltd mine geologists and the first three named authors in 1999 and 2000. Access to underground workings allowed the various mineralisation styles to be related to specific structures. In addition, sufficient structural information was collected from fault exposures to allow a statistical treatment of the data. A paragenetic description has been integrated within this structural framework and related to the regional carbonate stratigraphy determined for the Limestone Billy Hills. This work confirms the first-order structural control on sulphide mineralisation at Pillara and provides new constraints on structurally-controlled Zn-Pb mineralisation in the region.

## REGIONAL SETTING

The Lennard Shelf forms the northeastern margin of the Canning Basin where sediments onlap Precambrian crystalline rocks of the Kimberley Block (Figure 1). It is separated from the bulk of the Canning Basin by the Fitzroy Trough, a deep extensional basin formed during the late Devonian and early Carboniferous (Kennard et al., 1994). The Pillara Zn-Pb deposit is hosted by Famennian platform facies carbonate rocks on the northern margin of the Limestone Billy Hills. These rocks were deposited during back-stepping of the reef margin to the northeast and were overlain by basin-facies shales of the Gogo Formation (Playford, 1980). Sedimentation was coeval with northeast to southwest extension within the Fitzroy Trough, with major bounding faults located along the southwest margin of the Lennard Shelf (Kennard et al., 1994).

Two of these major bounding extensional faults, the Virgin Hills and Oscar Range Faults, are offset in a dextral sense by the Fossil Downs Graben, which has been interpreted as an accommodation zone by Dörling et al. (1996a). The Albatross Fault Zone is a zone of sinistral transtension formed along the eastern margin of the Fossil Downs Graben and which encompasses the Limestone Billy Hills, separating it from the northern Pillara Range. Seismic data indicate that extensional faults directly north of the Limestone Billy Hills strike northeast-southwest and dip to the northwest or southeast, creating a horst and graben structure (Dörling et al., 1995; Kemp and Wilson, 1980).

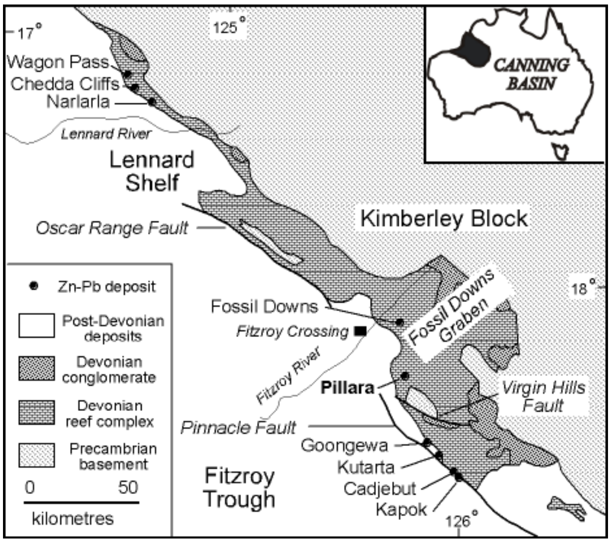


**Figure 1. Regional map showing the Lennard Shelf and the Pillara deposit modified after Playford (1980).**

There are three main structural styles in nearby outcrop (Dörling et al., 1996b): dominant, north-trending, sinistral oblique-slip faults containing limestone clasts cemented by calcite spar and sulphides, interpreted as Riedel shears; west to northwest-trending dextral oblique faults, and; northwest-trending domino faults with minor offset but containing sulphide minerals. Tension gash orientations and tectonic stylolites in outcrop indicate that $\sigma_1$ was orientated northwest-southeast, $\sigma_3$ northeast to southwest, and that $\sigma_2$ was near vertical. The orientation of $\sigma_1$ is considered to have been sub-vertical outside of the accommodation zone (Dörling et al. 1996b). The platform sequence is estimated to have been tilted between 10 and 20° to the northeast following deposition (Murphy et al., 1986; Dörling et al. 1996b). Symons and Arne (2005) conclude that most of the tilting of the sequence pre-dated base metal deposition based on paleomagnetic studies.

## LITHO-STRUCTURAL CONTROLS

In global terms, the Pillara deposit is hosted by a set of north-northeast-trending conjugate normal faults that bound a central graben plunging gently to the northeast (Figure 2). At the mine-scale each fault branch of the graben-bounding faults is made up internally of fault segments of about 200 to 300 m length that strike northeast and north-northeast and enclose an arcuate angle of about 20° to 25° to one another. The fault segments form overlap zones at their respective terminations that give rise to "mega clast" formation and strong veining which coincides with a lack of discrete fault gouge development. Kinematic indicators on all fault surfaces indicate dominantly dip-slip movement, although some evidence for strike-slip motion is locally evident. The above-mentioned internal fault geometry developed in a sinistral oblique-slip system facilitates greater movement on the more favourably orientated north-northeast fault segments (releasing bends) compared to the relative tighter northeast segments.

Extension increases from approximately 15% in the south to as much as 50% in the north of the graben (Figure 3). The complex array of faults is consistent with a northwest-southeast directed extensional stress field and a vertical $\sigma_1$ prior to minor tilting of the sequence to the northeast, suggested by the presence of sulphide stalactites plunging steeply to the southwest. Northwest-southeast extension was localised within a northeast-trending transfer structure within a regional northeast-southwest extensional regime.

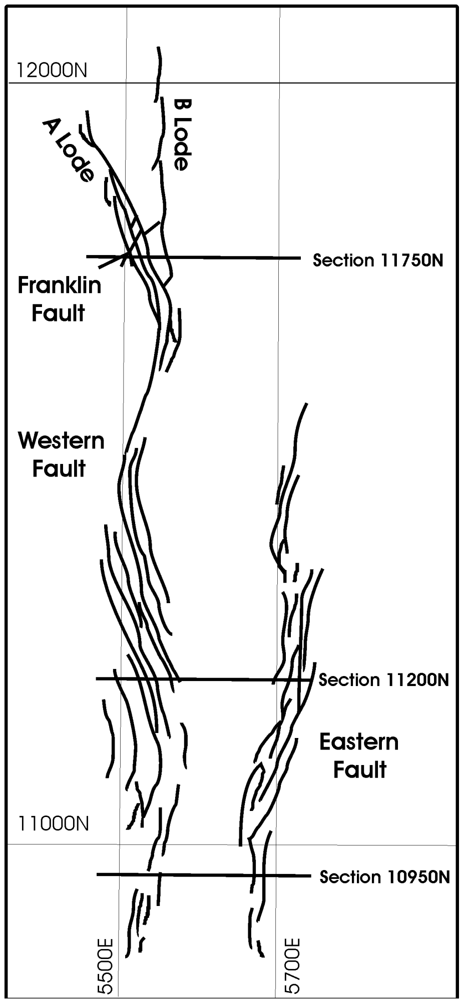


**Figure 2. Summary of fault traces projected to surface at Pillara based on back mapping as of January 2000. The positions of the cross sections in Figure 3 are also shown. Note that the mine grid is orientated 20° east of true north.**

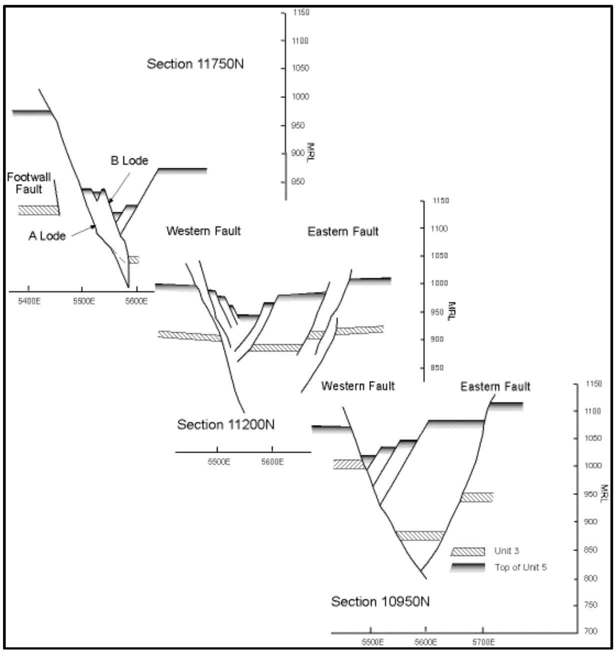


**Figure 3. Interpreted structural cross section viewed looking northeast. Locations are shown on Figure 2.**

Local controls on the development of mineralisation plunging shallowly to the northeast include dilation where faults steepen or overlap and where antithetic faults intersect the main bounding Western and Eastern Faults. Dilational zones are largely controlled by the orientation of fault segments and the intersections of faults with a competent fenestral limestone unit (Unit 5) and lower platform and bank facies (Unit 1). The intersection of north and northeast trending fault segments defines a steep, northerly plunge that appears to control high-grade orebodies in the F10 system (A Lode and B Lode).

## MINERALISATION STYLES

Mineralisation is dominantly located in tectonic breccia zones and open-space fill along faults, as well as in extensive hanging-wall hydraulic breccia zones localised by fault relays and intersections with antithetic faults. The latter grade outwards from rubble-breccia through mosaic breccia to crackle breccia and stockwork vein zones. Veins and breccias may show a history from early marine calcite cements through to pre-ore marcasite and calcite-cemented crackle breccia ($B_0$), to ore-stage breccias characterised by sulphide-cemented rubble breccias ($OB_1$) at times incorporating sulphide breccia clasts ($OB_2$), to post-ore breccias cemented by sparry calcite cement ($OB_3$). The ore textures and paragenetic sequence are consistent with introduction of the ore fluids during active fault movement with rapid precipitation into open cavities created during faulting.

The earliest generation of brecciation observed at Pillara are clast-filled Neptunian dykes of sedimentary origin. These are interpreted to have formed during syn-sedimentary faulting or differential compaction on the platform margin, and can contain clasts of the adjacent limestone, surrounded by horizontally bedded red/green siltstone of the overlying Virgin Hills Formation, or clasts of fibrous marine calcite cement, showing a radioaxial texture. They may be up to several metres across but are more typically less than 0.5 m in width, and can be traced for several hundred metres, particularly along the platform margin where they are best developed, often occurring every few metres across strike. The walls of these dykes are lined with marine fibrous cements, but the centres of the veins may consist of nearly the complete paragenetic sequence observed elsewhere in the deposit. Clasts of marine fibrous cement are cemented by sulphides where the veins have been brecciated. Neptunian dykes have been reactivated where they are orientated parallel to the main fault systems at Pillara, but they do not form a significant host for mineralisation.

Breccia-hosted sulphide mineralisation is both spatially and genetically associated with faulting. The footwalls of both the Western and Eastern Faults are typically characterised by a pre-ore crackle breccia ($B_0$) cemented by marcasite and calcite, the intensity of which decreases away from major fault segments. Crackle breccia is also found in the hangingwalls of the Eastern and Western Faults where it is gradational with the breccias described next.

The main ore-stage breccia ($OB_1$) varies from a rubble to mosaic to crackle breccia with increasing distance from fault planes, reflecting a decrease in the physical impact of faulting and hydraulic fracture intensity. It is best developed on the hangingwalls of the faults in a zone up to 5 m across. In places, clast size in the mosaic breccias exceeds 0.5 m to form a “megabreccia” before grading into crackle breccias. Mega breccia occurs in the fault segment overlap zones. The clasts are typically coated first with marcasite, followed by light to dark brown colloform sphalerite which may be intergrown with dendritic galena. Crystalline dark red sphalerite and euhedral galena developed slightly later in the paragenesis. White blocky calcite occludes the remaining intraclast voids. In some instances, marcasite lines intraclast voids and is overlain by internal sediment. White blocky calcite cement fills the remaining void space and locally replaces the internal sediment. Large cavities in the A Lode contain sphalerite stalactites that are cemented by white blocky calcite cement. The stalactites are inclined ~6$^{o}$ from vertical to the south, suggesting a minor tilt of the deposit to the north following mineralisation.

The early marcasite+calcite veining associated with crackle brecciation is locally offset by stylolites, some of which are mineralised, suggesting it pre-dated the maximum compressive stresses associated with burial and faulting. Crackle breccia and, locally, both sub-horizontal and sub-vertical stylolites occur within limestone clasts within ore-stage breccias indicating that deep burial, compressive stress and early crackle brecciation in part pre-dated main-stage sulphide mineralisation. Stylolites also define the margins of some high-angle veins, suggesting that local compressive stresses continued to exist following mineralisation. This observation is consistent with the findings of Dörling et al. (1996b) from outcrop in the Pillara Springs area indicating that horizontal stylolites and tensions gashes formed progressively during mineralisation.

Brecciation continued locally during the main ore-stage event ($OB_2$), as indicated by the presence of sulphide clasts, mainly consisting of colloform marcasite or sphalerite, cemented by sphalerite and galena, as well as blocky white calcite cement. Post-ore stage breccias are characterised by cementation of angular sulphide clasts by white blocky calcite cement.

Massive sulphide mineralisation up to 50 cm across occupies the main fault zones directly adjacent to the footwall. The paragenesis is similar to that defined previously for breccia in-fill, although fault gouge and micro-breccia containing angular clasts less than 1 cm across may be present. This massive ore tends to grade into rubble breccia in the hangingwall direction but is typically in abrupt contact with crackle breccia in the immediate footwall. The footwall contact is characterised by a slickenside surface.

Breccia veins or dykes consist of discrete breccia zones up to 1 m across orientated sub-parallel to major fault planes and dipping back toward the fault plane in an antithetic relationship. The veins typically contain $OB_1$ breccia displaying mosaic textures, but rubble and crackle textures are also observed. They appear to be developed in areas of slight flexure in fault plane dip, particularly in areas of local steepening where dip slip movement cannot be entirely accommodated within the fault plane.

Dilational veins are characterised by open-space-filling textures, namely colloform marcasite and sphalerite, along with dendritic galena and coarsely crystalline calcite spar. Some of these veins are purely tensional in origin, in that they have formed perpendicular to $\sigma_3$. Alternatively, dilation is also observed locally along the major faults where flexures in the fault planes have allowed for dilation during dip-slip.

## PARAGENESIS

Detailed petrographic analysis supports the general mineral paragenesis summarised in Figure 4, which is in agreement with previous studies. The earliest minerals introduced at Pillara include calcite and marcasite found in crackle breccias adjacent to faults, and lining dilational veins and re-activated Neptunian dykes. Early calcite and marcasite associated with crackle brecciation occurs in limestone clasts incorporated into fault breccias along the Eastern Fault, consistent with its introduction during the earliest stages of fault motion.

Marcasite is also commonly concentrated along low angle stylolites. A black, sooty iron sulphide is common in the B Lode area where it often lines mineralised cavities. This material has been described as melnikovitic pyrite, and it causes problems with excessive frothing in the flotation circuit. Marcasite also occurs later in the paragenesis in this area, often forming colloform bands up to several centimetres thick alternating with ore-stage calcite and light brown sphalerite. Locally, these marcasite bands have been brecciated and re-cemented by marcasite and may be overgrown by a more crystalline marcasite.

Early marcasite was typically followed by the deposition of light brown colloform sphalerite, generally forming layers up to several centimetres thick over limestone breccia clasts or lining cavities. This generation of sphalerite is often intergrown with skeletal galena near the intersection of the A and B Lodes, indicating rapid and simultaneous precipitation of lead and zinc, and may form pendulose bodies or stalactites along the upper margins of breccia cavities. The skeletal galena is typically associated with specific inclusion-rich growth bands in the sphalerite.

In thin section, the colloform sphalerite consists of alternating layers of colourless to red sphalerite, including zones with a purple colouration. Rarely, the zinc sulphide is anisotropic and displays "ice fern" textures suggestive of wurtzite. This colloform sphalerite is locally disrupted by brecciation and may be re-cemented by sphalerite or zoned ore-stage calcite.

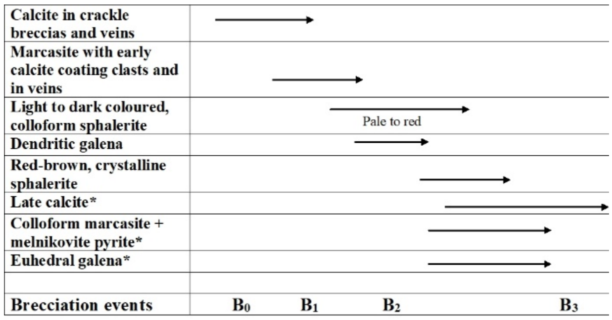


**Figure 4. Paragenetic sequence for the Pillara Zn-Pb deposit. * - best developed in dilational cavities.**

Euhedral galena crystals up to several centimetres across are associated with crystalline sphalerite late in the paragenetic sequence, consistent with a transition from rapid mineral deposition from a supersaturated ore fluid to a saturated solution from which large crystals can grow. Galena and sphalerite crystals are overgrown by a generally clear, blocky calcite cement that fills much of the remaining cavity space.

This general paragenetic sequence is locally repeated, for example in the B Lode, and may be truncated by brecciation, in which case minerals later in the paragenesis act as cements. Internal sediment can be found at the base of some breccia cavities where it pre-dates in-filling by the clear, blocky calcite cement. The main sulphide found within the internal sediments is well-formed cubic pyrite. Thus, the bulk of the calcite observed at Pillara is interpreted to be of post-ore origin. Ore-stage calcite tends to be cloudy with a weak zoning in thin section and to locally have an obvious prismatic habit. It is coincident with the deposition of regional moderately brightly luminescent calcite cement (Figure 5). Unlike much of the southeastern Lennard Shelf, dolomite is rare at Pillara and in the Limestone Billy Hills.

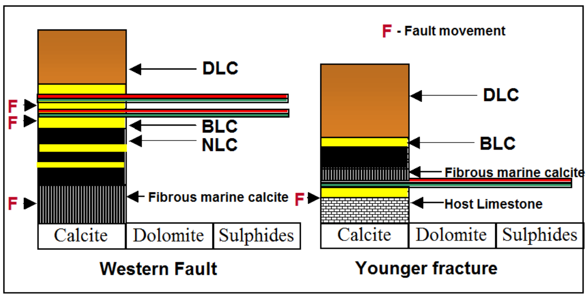


**Figure 5. Carbonate cementation sequence for Pillara Zn-Pb deposit in the Limestone Billy Hills. DLC – dull luminescent cement; BLC – bright luminescent cement; NLC – non-luminescent cement.**

## ROCK STRENGTH TESTING

Previous studies (Murphy et al., 1986) had noted the preference of certain units within the platform stratigraphy to act as a host for sulphide mineralisation. Unit 5 is preferentially mineralised along both the Western and Eastern faults, whereas the A and B Lodes are hosted by Units 1 and 2.

The previously available rock strength data for the Pillara mine were collected without reference to the established stratigraphy, and so are insufficient to determine the influence of rock mechanics on the distribution of ore zones. Accordingly, a representative suite of samples was collected from diamond drill core and subjected to uniaxial compressive strength testing using an Isotron compressive testing machine at the Western Australian School of Mines. Most samples came from a single deep stratigraphic drill hole into the core of the graben between the Western and Eastern faults (PD265), with the exception of samples from Unit 7 and the Gogo Formation, which were not intersected by this drill hole. Two sets of samples were collected. One set contained no discontinuities within the core, with the exception of bedding in the basinal sedimentary rock samples, whereas a second set contained typical discontinuities such as stylolites.

The uniaxial compressive strength of the samples ranges from a low of 39 to 51 MPa for the Virgin Hills and Gogo Formations, to values of 146 and 160 MPa in Units 4 and 3, respectively. The limestone samples typically range between 100 and 150 MPa, which is high for typical limestone. Of the purely limestone samples, Units 1 and 5 gave the lowest uniaxial compressive strengths of samples containing no discontinuities, consistent with their displaying the greatest tendency to fail during faulting. These units, along with Unit 6, also tended to fail by axial splitting, whereas the remaining samples either failed through multiple cracking or through shear failure. Samples from Unit 5 and Unit 6 contained low angle stylolites that have clearly reduced the uniaxial compressive strength of the samples even further.

The Young's Modulus values for the limestone samples range between 40 and 74 GPa, which is again high for typical limestone and indicates strongly elastic behaviour under stress. The lowest limestone value occurs in Unit 5 but may have been affected by the presence of stylolites. Young's modulus values for the Virgin Hills and Gogo Formations are considerably lower than those for the limestone samples and, along with the uniaxial compressive strengths of these samples, are slightly lower than expected for typical shale and siltstone samples. There appears to be little systematic variation in Poisson's Ratio among the limestone samples.

Rock testing therefore suggests that the preference of stratigraphic Units 5 and 1 to host sulphide mineralisation is due to their lower uniaxial compressive strengths compared to the other limestone units in the mine area. This has resulted in their behaving in a brittle, rather than elastic, fashion during faulting, and in the creation of structurally controlled fluid pathways in what are otherwise generally low-permeability limestone units. Failure in all limestone units at Pillara is likely to have been enhanced by the presence of pre-existing discontinuities, such as stylolites and Neptunian dykes.

## CONCLUSIONS

Examination of underground exposures and diamond drill core indicates that sulphide mineralisation at Pillara occurred during the final stages of prolonged deformation along a set of segmented, north-northeast-trending, en echelon conjugate normal faults formed in a northwest-southeast directed extensional environment. The earliest mineralisation consisted of marcasite and calcite that pre-dated stylolite formation and was followed by the precipitation of colloform marcasite and sphalerite, the latter intergrown with dendritic galena, into cavities formed during active faulting. Textures indicate that sulphide precipitation was initially rapid from an ore solution supersaturated with respect to ZnS and PbS, but gradually slowed to allow the formation of crystalline sphalerite and galena. Minor faulting continued after the main ore-stage event, resulting in the cementation of sulphidic breccia fragments by other sulphide minerals as well as blocky calcite.

Moderately northward-plunging mineralisation along the Western and Eastern Faults was mainly controlled by the intersection of these structures with stratigraphic units 1 and 5, and by changes in fault dip across these units. These units show lower uniaxial compressive strengths than the other limestone units at Pillara in the absence of discontinuities, and so were more likely to fail in a brittle manner. A high grade, steeply plunging ore body at the intersection of the A and B Lodes is broadly coincident with the plunge defined by the intersection of north and northwest trending fault sections.

Structural investigations indicate that the Pillara deposit formed shortly after deposition of the host carbonate sequence during active extension in the nearby Fitzroy Graben, consistent with a Late Devonian to Early Carboniferous timing for ore deposition determined by carbonate cement stratigraphy, radiometric dating and paleomagnetism.

## ACKNOWLEDGEMENTS

The authors would like to thank former Pillara mine staff from Western Metals Ltd, particularly Peter Muccilli, for their assistance. This project was funded by an Australian Research Council Small Grant to Dennis Arne and Robert Fagan through Curtin University.

## REFERENCES

Dörling, S.L., Dentith, M.C., Groves, D.I. and Vearncombe, J.R., 1996a, Mississippi Valley-type deposits of the southeast Lennard Shelf of the southeast Lennard Shelf: An example of the interplay of extensional deformation, sedimentation and mineralisation. In Carbonate-hosted Lead-zinc Deposits, Sangster, D.F. (ed), Society of Economic Geologists Special Publication No. 4, 96-111.

Dörling, S.L., Dentith, M.C., Groves, D.I., Playford, P.E., Vearncombe, J.R., Muhling, P., Windrim, D., 1996b, Heterogenous brittle deformation in the Devonian carbonate rocks of the Pillara Range, Canning Basin: Implications for the structural evolution of the Lennard Shelf. Australian Journal of Earth Sciences, 43, 15-29.

Dörling, S.L., Dentith, M.C., Playford, P.E. and Vearncombe, J.R., 1995, Regional structures of the Fitzroy Trough and Lennard Shelf. In J.R. Vearnecombe et al. (eds.), Zinc-lead Mineralization on the Southeast Lennard Shelf, Canning Basin, Western Australia, Society of Economic Geologists Guidebook Series Volume 23, 9-50.

Kemp, G.J. and Wilson, B.L., 1990, Seismic expression of Middle to Upper Devonian reef complexes, Canning Basin. The Australian Petroleum Exploration Association Journal, 30, 280-289.

Kennard, J.M., Jackson, M.J., Romine, K.K., Shaw, R.D. and Southgate, P.N., 1994, Depositional sequences and associated petroleum systems of the Canning Basin, WA. In P.G. Purcell and R.R. Purcell (eds.), The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 657-676.

Murphy, G.C., 1990, Lennard Shelf lead-zinc deposits. In Geology of the Mineral Deposits of Australia and Papua New

Guinea, Hughes, F.E. (ed), The Australasian Institute of Mining and Metallurgy, 1103-1109.

Murphy, G.C., Bailey, A. and Parrington, P.J.,1986, The Blendevale carbonate-hosted zinc-lead deposit, Pillara, Kimberley region, Western Australia. In Berkman, D.A. (ed.), 13th Congress of Mining and Metallurgical Institutions, volume 2, 153-161.

Playford, P.E., 1980. Devonian "Great Barrier Reef" of Canning Basin, Western Australia. American Association of Petroleum Geologists Bulletin 64, 814-840.

Symons, D.T.A. and Arne, D.A., 2005, Paleomagnetic constraints on Zn-Pb ore genesis of the Pillara Mine, Lennard Shelf, Western Australia. Mineralium Deposita, 39, 944-959.

Vearncombe, J.R., Dentith, M., Dörling, S., Reed, A., Cooper, R., Hart, J., Muhling, P., Windrim, D. and Woad, G., 1995, Regional and prospect-scale fault controls on Mississippi Valley-type Zn-Pb mineralisation at Blendevale, Canning Basin, Western Australia. Economic Geology, 90, 181-186.

Vearncombe, J.R., Chisnall, A.W., Dentith, M., Dörling, S., Rayner, M.J. and Holyland, P.W., 1996, Structural controls on Mississippi Valley-type mineralisation, the southeast Lennard Shelf, Western Australia. In Carbonate-hosted Lead-zinc Deposits, Sangster, D.F. (Editor), Society of Economic Geologists Special Publication No. 4, 74-95.