AGSO Journal of Australian Geology & Geophysics, 17(4), 115–120

Lennard Shelf Mississippi Valley-type (MVT) Pb–Zn deposits, Western Australia

S.L. Dörling[1], D.I. Groves[2] & P. Muhling[3]

[1]RGC Exploration, 89 Burswood Rd., Victoria Park, Perth, WA 6100, Australia. [2]Key Centre for Strategic Mineral Deposits, Department of Geology and Geophysics, University of Western Australia, Nedlands, Perth, WA 6907, Australia. [3]BHP Exploration, 3/3 Plain St, East Perth, WA 6004, Australia.

EXPLORATION MODEL

Examples

SE Missouri, Pine Point, San Vicente, Silesia, Polaris, Lennard Shelf

Target

- Characteristically, small discrete deposits forming a mineral district.
- Deposit range: 2–20 Mt.
- Average: 2–4 Mt @ 12% Pb + Zn.
- Locally low–moderate Ag levels.

Mining and treatment

- Competent carbonates ensure relatively low cost mining.
- Tabular ore bodies with uniform grades, allowing cost-effective assessment and mining, and steeply dipping, disc-like ore bodies, imposing difficulties in assessment and mining.
- Coarse grain size and simple mineralogy.
- Low pyrite content in ore means simple processing, giving clean concentrate which attracts no penalties.
- Very high recovery rates, > 95%.

Regional geological criteria

- Rift-related intracontinental basin.
- Basin margin characterised by normal faults and accommodation zones—extensional tectonic setting.
- Deposits located along margins of sedimentary basins and intrabasin highs.
- Proximity to syn-sedimentary faults.
- Hosted within platform or marginal-slope carbonate rocks.
- Evaporites may provide target horizons.
- Generally, the only style of mineralisation present in the province.

Mineralisation features

- Stratabound and hosted in faults and hydrothermal cavities.
- Stratabound, rhythmically banded ore with replacement of primary sedimentary features.
- May be associated with dolomite halo.
- Calcite most common gangue mineral.
- Fault and dissolution breccia ore.

Local geological criteria

- Half-graben structures and basement highs along basin margin are linked via extensional normal faults.
- Deposits located at or near platform margin, proximal to basin interior.
- Accommodation delineates compartments of sedimentation and fluid-flow.
- Normal faults and accommodation zones can be prospective.
- Ore formation/emplacement is temporally associated with extensional deformation.
- Absence of any igneous activity.

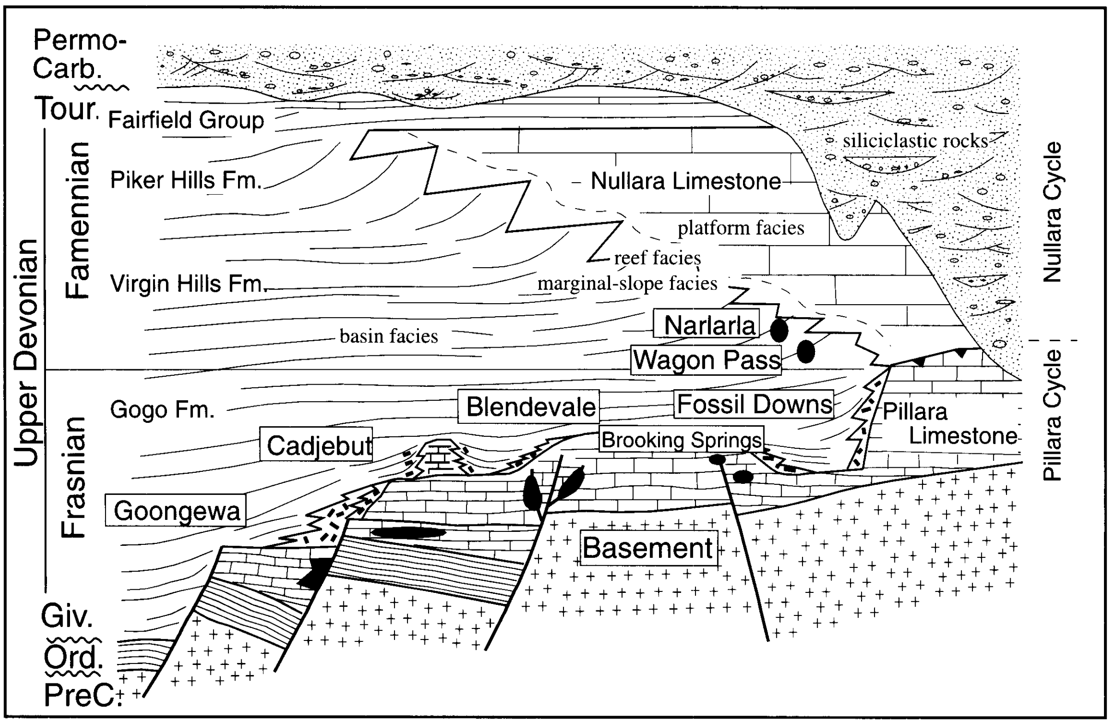

Figure 1. Schematic illustration of the relationships between faults, sedimentary facies and MVT mineralisation on the Lennard Shelf (after Playford 1980).

Alteration

- Some deposits may be surrounded by a pyrite/marcasite halo.
- Generally, no host-rock alteration present; however, host rocks may be dolomitised.

Surficial geochemical criteria

- Prospects well defined by regional stream sediment, soil and gossan sample anomalies.
- However, these anomalies represent regional targets, not drill targets.

Geophysical criteria

- Gravity and aeromagnetic surveys can be used to delineate regional structure and basement highs.
- Seismic surveys can define structural and sedimentological evolution of the depositional setting.
- Some deposits associated with a marcasite halo which has a strong IP response.

Fluid chemistry and source

- Salinity from fluid inclusions varies from 10 to 25 wt% NaCl equivalent.
- Conodont Alteration Indices indicate that host rocks have not been exposed to temperatures higher than 70°C for extended periods.
- Fluid inclusions indicate ore-forming temperatures of 70–130°C.
- S isotope data indicate mixing between basin-derived, base-metal-carrying fluid and an in-situ S source (e.g. evaporites).
- Pb isotope data indicate base metals sourced from both distal, mature fine-grained siliciclastic sediments and proximal, less mature sediments.

Comments on genesis

- MVT deposits of the Lennard Shelf probably represent one end member in the spectrum of MVT ore-forming settings, which ranges from extensional to compressional tectonic settings.
- The process of ore formation is the result of interaction between deformation, sedimentation and facies-distribution controlling fluid migration.
- Extensional deformation generates sedimentary compartments.
- Reactivation of regional extensional faults exerts a major control on fluid migration from the basin towards its margins.
- Each sedimentary compartment generates fluids with varying geochemical signatures.
- Faults allow rapid ore-fluid migration.

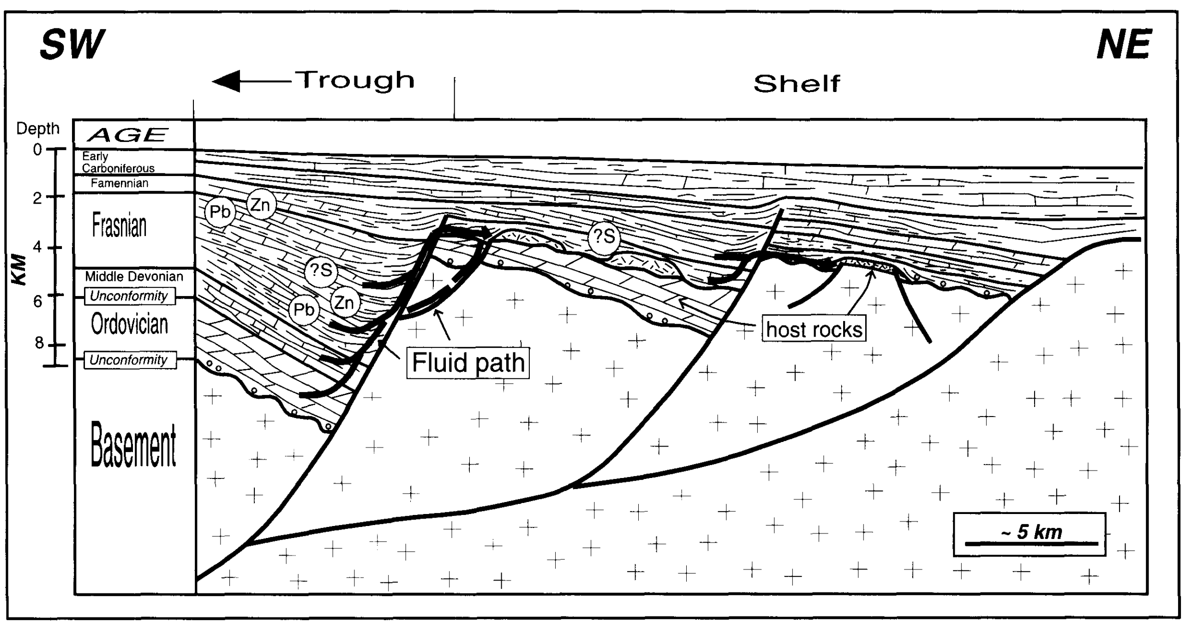

Figure 2. Interpreted plumbing system for basinal brines, metal and sulphur. Metal-carrying fluids are interpreted to have been generated in the deeper part of the trough and to have migrated towards the shallower shelf.

Introduction

Mississippi Valley-type (MVT) Pb–Zn deposits owe their name to the fact that many of the classical mining districts are located in the drainage basin of the Mississippi river, central USA. There are also important districts of this deposit type in Europe, northern Africa, South America, Canada and Australia. The Lennard Shelf of Western Australia, the only Australian MVT Pb–Zn mining district, has a relatively young mining history, compared with the established Australian base-metal producing districts of the stratiform sediment-hosted type (e.g. Mt Isa). However, the Australian deposits have the potential to become a significant future supplier of Pb and Zn.

Mississippi Valley-type mining districts generally contain up to 300 small (1–3 Mt) deposits (Sangster 1990). Mineralisation is epigenetic and hosted in carbonate rocks of reefal or platformal origin, generally deposited along the margin of sedimentary basins. The carbonate rocks are clean limestone or dolostone. The deposits are generally stratabound or hosted in deformational structures and show no association with igneous activity.

Geological evolution and setting of the Fitzroy Trough/ Lennard Shelf area

The Lennard Shelf formed during the Late Palaeozoic along the northeastern margin of the Fitzroy Trough, which is a well-defined rift system trending west–northwest in the northern half of the Canning Basin. The southern margin of the rift is formed by the Broome Arch. The Canning Basin is a Phanerozoic intracratonic basin which separates the Archaean Pilbara Block to the southwest from the Proterozoic Kimberley Block to the northeast. During its evolution, the Canning Basin was subject to several successive periods of crustal stretching and subsidence: Late Ordovician–Early Silurian, Middle Devonian–Early Carboniferous, and Late Carboniferous/Early Permian–Early Triassic (Brown et al. 1984, Kennard et al. 1994). The Middle Devonian–Early Carboniferous phase of crustal stretching, referred to as the Pillara Extension (Kennard et al. 1994), led to the formation of the Fitzroy Trough and Lennard Shelf rift system, which is 100–150 km wide and 800 km long.

Stratigraphy of the Fitzroy Trough and Lennard Shelf

The Fitzroy Trough contains more than 10 km of sedimentary rock of Early Ordovician–Cretaceous age (Drummond et al. 1991, Kennard et al. 1994). The age and thickness of the lowermost rocks are not known, owing to their deep burial. However, sedimentary rocks of Early Ordovician age, deposited in a shallow-marine to continental environment, overlying crystalline basement on the Lennard Shelf, mark the onset of sedimentation on the Lennard Shelf (Fig. 1), and suggest that rocks of similar age can be expected in the trough. An angular unconformity of 10–15° separates Lower Ordovician rocks from upper Middle Devonian sedimentary rocks on the Lennard Shelf. During the Pillara Extension, a thick succession of clastic sediments accumulated in the rift. Interpreted seismic data suggest that up to 6 km of sediments (Dörling et al. 1995) were deposited in the Fitzroy Trough, whereas only 1.5–2.5 km of shallow-marine carbonates and clastic sediments were deposited on the shelf (Playford 1980).

The Devonian–Carboniferous sedimentary succession on the Lennard Shelf consists of a second-order cycle and is broadly divided into a transgressional period (Givetian–Late Frasnian) with retreating platform margins, and a regressional period (Late Frasnian–Tournasian) with prograding platform margins (Kennard et al. 1994, George et al. 1995). This sedimentary succession is the result of contemporaneous extensional deformation and eustatic sea level changes during the Pillara Extension. During this period, carbonate platforms developed on basement highs created by horsts and the high points of hanging-wall blocks rotated on listric faults. Hence, platform margins commonly coincide with basement faults active during deposition (Dörling et al. 1996). Generally, the margin is marked by a change from shallowly dipping carbonate rocks of the platform to more steeply dipping carbonate debris slopes, which thicken to deeper water carbonate–siliciclastic facies on the Lennard Shelf and adjacent part of the Fitzroy Trough (Playford 1980). In places, the margin may also show a narrow (<10 m wide) reef facies of clean carbonate rocks.

Following a period of regional uplift and erosion during the mid-Carboniferous, the area underwent another phase of subsidence, during which a thick succession (>4 km in the Fitzroy Trough) of siliciclastic sediments was deposited. Late Cretaceous uplift and erosion have left only remnants of Permian siliciclastic rocks on the shelf area.

Structure of the Fitzroy Trough and Lennard Shelf

Deep seismic investigations show that the northwestern part of the Fitzroy Trough is a classic asymmetrical rift, controlled by a crustal-scale detachment zone which dips north, away from the Fenton Fault (Drummond et al. 1991). In the northwest, as a result, the northeastern margin is a hinge line, whereas the southwestern margin is defined by the normal shallowly dipping Fenton Fault. The geometry of the Fitzroy Trough changes along strike across sub-orthogonal accommodation zones (Drummond et al. 1988, Vearncombe et al. 1995, Dörling et al. 1996), which offset both margins of the rift.

Detailed studies (Dörling 1996) show that the southeastern Fitzroy Trough/Lennard Shelf area is dominated by several parallel and en-echelon northwest-trending listric normal faults, which are offset by accommodation zones. These accommodation zones had a profound influence on drainage from the hinterland and distribution of shelf and basin facies sediments. Sediments accumulated in half-grabens in the hanging walls of rotated basement blocks.

MVT deposits of the Lennard Shelf

The Lennard Shelf MVT mining district currently has two operating Pb–Zn mines, two deposits in the initial stages of development, and a number of prospects (e.g. Ringrose 1989, Murphy 1990). Historical mining in the area occurred early this century at the Narlarla deposit, where 11033 t of ore at 23.2% Pb, 30.9% Zn and 162 g/t Ag was mined (Ringrose 1989). The deposits currently mined are the Cadjebut deposit (initial geological resource of 3.2 Mt at 14% Zn and 4.4% Pb) and the Goongewa (formerly known as the 12 Mile Bore) deposit, with a geological resource of 2.4 Mt at 10% Zn, 2.7% Pb and 38 g Ag (Murphy 1990). The Blendevale (with indicated resources of 20 Mt at 8% Zn, 2.5% Pb and 17 g/t Ag) and Kapok (with 2.8 Mt at 9.6% Zn, 7.9% Pb and 14 g/t Ag) deposits are currently being developed. Other prospects are Fossil Downs, Brooking Springs and Wagon Pass.

Features of the Lennard Shelf MVT deposits

Relationships of ore deposits to local stratigraphy and structure

Givetian to Famennian reefal complexes of the Lennard Shelf represent the only coherent MVT province in Australia, although individual deposits occur at Admiral Bay, in Ordovician carbonate rocks, on the edge of the Willara Sub-basin in the southern half of the Canning Basin (McCracken 1994), and at Sorby Hills (Ringrose 1989), where mineralisation is hosted in Lower Carboniferous carbonate rocks of the Bonaparte Gulf Basin. To date, most of the known deposits are situated along the southeastern portion of the Lennard Shelf in or near faults, many of which occur adjacent to the transition from platform to marginal-slope facies (Fig. 1). Lead–zinc ores generally include sphalerite, galena and sparry calcite with minor dolomite, marcasite and pyrite (Lambert & Etminan 1987). At Blendevale, Pb–Zn mineralisation is largely hosted in a set of conjugate extensional, north–northeast-trending oblique-slip faults that cut the western margin of the Limestone Billy Hills atoll block at an acute angle. Fault-hosted mineralisation shows evidence of multiple brecciation and precipitation. Faults are mineralised over a strike-length of >1.5 km at Blendevale. The host rocks surrounding the deposit show no evidence of hydrothermal alteration or dolomitisation. The Goongewa deposit is hosted in platform carbonate rocks in the hanging wall of the Cadjebut Fault. The deposit is described as a hydrothermal cavity-replacement ore-body (Bradley 1994) and has a dolomite halo. The Cadjebut and Kapok deposits are both related to the regional Cadjebut Fault. Whereas the Kapok deposit is completely hosted within a splay structure off the Cadjebut Fault, only an indirect link exists between the Cadjebut orebody and the Cadjebut Fault. However, a genetic interrelationship between the Cadjebut orebody and its structures is implied by the location of the orebody near the platform margin and corresponding lithofacies types, its proximity (<100 m) to a regional fault, and the direct association with minor splays related to the Cadjebut Fault. The deposit is stratabound and surrounded by a marcasite halo, and is described as an evaporate-replacement orebody (Tompkins et al. 1994a). Two ore types predominate in the mine: breccia ore, ascribed to solution collapse (Klopper 1993), and rhythmically banded ore ascribed to replacement of primary sedimentary fabric (Tompkins et al. 1994a). The Kapok deposit is similar to the Blendevale deposit in that it is fault and breccia-hosted.

Geochemical signatures of the deposits

Temperatures, salinity, conodont alteration data. Fluid inclusions in sphalerite and calcite of the Lennard Shelf Pb–Zn deposits contain dense, saline, aqueous fluids, commonly with hydrocarbons (Etminan & Hoffman 1989). The total dissolved salts range from 5 to 25 wt% and the predominant ions are Cl^-, Na^+ and Ca^{2+}. Homogenisation temperatures are generally in the range of 70–125°C (Lambert & Etminan 1987, Tompkins et al. 1994b). Conodont Alteration Index (CAI) studies, conducted to assess thermal alteration of the carbonate rocks in the immediate vicinity of the ore deposits, indicate that permeable strata through which ore fluids could have passed have not been heated above 70°C (Ringrose 1989). This discrepancy between ore-fluid temperatures and CAI temperatures suggests rapid migration of ore brines through faults to the depositional site.

Hydrocarbons, sulphur and lead isotopes. Hydrocarbons, and sulphur and lead isotope studies provide important insights into the composition and origin of mineralising fluids that lead to the formation of MVT deposits.

Etminan & Hoffman (1989) compared the maturity of hydrocarbons from fluid inclusions in sulphides and diagenetic carbonate cements with those of crude oils from the basin. Hydrocarbons in the MVT deposits are more mature than those in the adjacent host rocks and different from those of oil-producing strata in the basin in that they show different maturation levels. Furthermore, these authors detected differences in the biomarker composition of hydrocarbons in fluid inclusions, not only between each Pb–Zn prospect, but also compared with hydrocarbons in both organic-rich strata and oils from the central Fitzroy Trough. This led them to suggest that the base-metal-carrying fluids originated from multiple deep sources containing organic-rich strata.

Sulphides from MVT deposits on the Lennard Shelf show a relatively wide range in $\delta^{34}S$ isotope composition for each deposit (Lambert & Etminan 1987), with partial overlap between the signatures of all the deposits. However, most of this spread relates to the wide range in values of Fe sulphides, which have $\delta^{34}S$ values that are typically higher than associated galena and sphalerite in the same deposit, suggesting that they formed separately. Lambert & Etminan (1987) recognised an increase in $\delta^{34}S$ for Pb and Zn sulphides from the Cadjebut deposit, in the southeast, to the Wagon Pass and Narlarla deposits, in the northwest, and suggested different sources with distinctive S isotope compositions. An additional distinction can be made between the larger deposits (Cadjebut, Blendevale), which show $\delta^{34}S$ compositions closer to those of Upper Devonian evaporites than those of the smaller deposits (Fossil Downs to Narlarla), which are depleted in $\delta^{34}S$.

Lead isotope data from Cadjebut, Goongewa, Blendevale, Fossil Downs, Brooking Springs, Wagon Pass and Narlarla are very radiogenic, a feature that is characteristic of many MVT deposits worldwide (Vaasjoki & Gulson 1986). These deposits and prospects have very different Pb isotope compositions (Edwards 1984, Vaasjoki & Gulson 1986), which show a systematic increase in radiogenic lead along the Lennard Shelf in a northwesterly direction from Cadjebut to Wagon Pass, a feature first recognised by Vaasjoki & Gulson (1986). In addition, the deposits in the northwest, such as Wagon Pass, display a more heterogeneous signature than those in the southeast. Both these features imply that the Pb isotope fields relate to the geographic position of the deposits and that each deposit taps a distinct Pb reservoir (sediment package). Vaasjoki & Gulson (1986) suggested that the variation in the amount of radiogenic Pb reflects proximity of ores to either a deep sedimentary basin or crystalline basement. The highly radiogenic and isotopically heterogeneous Wagon Pass deposit occurs only a few kilometres from the margin of the Proterozoic basement, within an area of relatively little syn-sedimentary tectonism, which resulted in a thin sedimentary succession, thickening only gradually to the southwest. The southeastern deposits, however, from Brooking Springs to Blendevale and Cadjebut, are characterised by more homogeneous Pb isotopic values. All these deposits occur in the hanging wall strata of major syn-sedimentary faults that confine thick sedimentary sections, interpreted to be the source of Pb. This is consistent with the idea of Vassjoki & Gulson (1986) that thick sediment accumulations allowed the homogenisation of Pb through prolonged mechanical and geochemical reworking.

Data points for individual deposits plot as clusters in the $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ plots rather than as a point on the average basement-Pb isochron. This is interpreted to reflect interaction between basinal fluids and basement rocks and/or their derived immature sediments with different Pb isotope compositions (Dörling 1996). Considering the structure of the Fitzroy Trough, there are two potential reservoirs of Pb that can be distinguished: sediments in distal, deeper parts of the trough and sediments in isolated half-grabens near its margin.

It is argued (Dörling 1996) that the signature in the Pb isotope of ore sulphides in individual deposits could be due to mixing of Pb from the two different reservoirs. Fluids infiltrating along more continuous deeper paths in the trough dissolved isotopically homogeneous Pb, whereas more shallowly adventive fluids dissolved more heterogeneous Pb from more locally derived sediments in marginal half-grabens. During fluid migration out of the basin towards the sites of mineralisation, the relatively homogenous Pb signature of fluids will be overprinted as fluids mix near the trough margin with locally derived Pb of a more heterogenous signature. This process is envisaged to have led to the complex Pb isotope signature of the Lennard Shelf province.

Genesis of ore deposits

Fluid flow mechanism and ore emplacement

Structural analysis of the southeastern Fitzroy Trough indicates a rift-setting which features a complex margin with numerous half-graben compartments bounded by accommodation zones linked to the central trough (Dörling 1996). Syn-depositional faults created the compartments, which acted as local depocentres containing up to 6 km of pre-mineralisation sedimentary strata (including up to 5 km of Middle–Late Devonian rocks), which are interpreted to reflect relatively rapid sedimentation and form a potential source of metals. Diagenetic studies (McManus &

Wallace 1992) and recent absolute-age determinations on ore-stage calcite and sphalerite (Brannon et al. 1995, Christensen et al. 1995) place the ore-forming event in the latest Devonian–earliest Carboniferous. This age for mineralisation overlaps the waning stages of Pillara Extension in the Fitzroy Trough.

Fluid inclusion and isotope signatures, mineral and host rock compositions, temperatures of formation, and the association with hydrocarbons are features of the Lennard Shelf deposits which are common to many MVT districts (Leach & Sangster 1993). However, the unambiguous association of deposits in this district with faults and the formation of mineralisation at the same time as extensional deformation are uncommon, and widen the spectrum of settings and fluid-flow mechanisms that have to be considered for MVT deposit formation.

As constrained by the structural, sedimentological and geochemical data, it is likely that brines from deeper parts of the trough mixed with fluids within marginal half-graben depocentres during fluid flow outwards and upwards towards active extensional faults at the margin (Fig. 2). Rapid fluid flow along faults precluded any thermal equilibration with country rocks. Ore precipitation in faults and related structures probably occurred as a result of cooling, whereas stratabound ore probably formed as a result of fluid mixing and evaporite replacement.

Several conceptual models have been proposed to explain fluid expulsion out of sedimentary basins. With the geological constraints on the Lennard Shelf, none of the concepts proposed for the North American MVT deposits can be applied, e.g. gravity-driven (Sverjensky & Garven 1992) or tectonically driven (Oliver 1986) fluid flow. The driving force for mineralisation on the Lennard Shelf is interpreted to be rapid subsidence and sedimentation in the trough, leading to overpressuring of sediment-trapped water and, possibly, oil and gas through compaction (Dörling et al. 1995). Episodic faulting is interpreted to have released pulses of brines carrying Pb–Zn.

Criteria for exploration

Key exploration criteria for Lennard Shelf-type MVT deposits

The Lennard Shelf MVT deposits are characterised by a number of geological features that can be incorporated into regional reconnaissance and focused exploration activity in prospective areas. Potential host units are carbonate rocks near the edges of platforms where major faults lead from the source rock regions of deep depocentres up to basement highs. Fluid focusing and/or ore deposition are related to structures whose geometry reflects a linked system with both syn-depositional and syn-mineralisation components. At the local scale, facies variations such as evaporites may be important in the localisation of ore.

Exploration tools at the regional and local scale

The analysis of regional geophysical data is the most important exploration tool in identifying prospective geological settings. Combined seismic, aeromagnetic, and gravity surveys are very powerful for regional analysis. Aeromagnetic and gravity surveys can identify features that control mineralisation, such as basement highs, carbonate platforms or mounds, and faults (Murphy 1990). Seismic reflection data, in particular, provide detailed depth information on structures, structural evolution, sedimentation and likely fluid and metal source areas.

Regional stream-sediment sampling, with follow-up soil, rock chip and gossan sampling, together with geological mapping, can define areas on which to focus exploration.

At the prospect scale, MVT deposits are difficult geophysical targets. IP surveys have proved to be an important semi-regional tool in exploration for MVT systems rich in Fe (marcasite), such as Cadjebut and Blendevale (Isles et al. 1987). However, geophysics, like detailed surface geochemistry and geology, does not provide drill targets, but delineates favourable areas for systematic grid drilling, which, although slow and expensive on a regional scale, is the most effective way to test anomalies. Grid drilling has proved the most successful method in exploring for MVT deposits on the Lennard Shelf, as well as in some North American districts.

Acknowledgments

The data in this paper were gathered largely as a result of MERIWA Project 201. We are grateful to M. Dentith, B. Eisenlohr, M. Rayner, A. Reed, L. Tompkins and J. Vearncombe for their contributions. We have also benefited from discussions with A. George, S. McCracken, P. Playford, M. Wallace and D. Windrim. We thank BHP Minerals Exploration for financial support. S. Dörling was sponsored by OPRS and URS scholarships.

References

Bradley, A.J., 1994. The origin of Mississippi Valley-type sulphide mineralisation at Twelve Mile Bore, Lennard Shelf, Western Australia: B.Sc. Hons thesis, Department of Geology, University of Melbourne, 76 pp (unpublished).

Brannon, J.C., Cole, C.C. & Podosek, F.A., 1995. Can all Mississippi Valley-type (MVT) ore deposits be radiometrically dated? [abstract]: Society of Economic Geologists, International Field Conference on Carbonate-Hosted Lead–Zinc Deposits, St. Louis, MO., 27–29.

Brown, S.A., Boseriol, I.M., Jackson, K.S. & Spence, K.W., 1984. Geological evolution and petroleum prospects. In: Purcell, P.G. (editor), The Canning Basin, WA. Proceedings of the Geological Society of Australia/Petroleum Exploration Society of Australia Symposium, Perth, 95–96.

Christensen, J.N., Halliday, A.N., Vearncombe, J.R. & Kesler, S.E., 1995. Testing models of large-scale crustal fluid flow using direct dating of sulfides: Rb–Sr evidence of early dewatering and formation of MVT deposits, Canning Basin, Australia. Economic Geology, 90, 877–884.

Dörling, S.L., 1996. Structural evolution of the southeast Lennard Shelf and Fitzroy Trough, W.A. during the Pillara Tectonic Phase: implications for facies distribution and MVT Pb–Zn mineralisation. Ph.D. thesis, Key Centre for Strategic Mineral Deposits, Department of Geology and Geophysics, University of Western Australia, Perth, 180 pp (unpublished).

Dörling, S.L., Dentith, M.C., Groves, D.I. & Vearncombe, J.R., 1995. Extensional, synsedimentary deformation and compaction-driven fluid-flow: an alternative mechanism for MVT deposit formation on the Lennard Shelf, Western Australia [abstract]. Society of Economic Geologists, International Field Conference on Carbonate-Hosted Lead–Zinc Deposits, St Louis, Missouri, 76–80.

Dörling, S.L., Dentith, M.C., Groves, D.I., Playford, P.E., Vearncombe, J.R., Muhling, P. & Windrim, D., 1996. Heterogeneous brittle deformation in the Devonian carbonate rocks of the Pilbara Range, Canning Basin: implications for the structural evolution of the Lennard Shelf. Australian Journal of Earth Sciences, 43(1), 14–22.

Drummond, B.J., Etheridge, M.A., Davies, P.J. & Middleton, M.F., 1988. Half-graben model for the structural evolution of the Fitzroy Trough, Canning Basin, and its implications for resource exploration. The APEA Journal, 28(1), 76–86.

Drummond, B.J., Sexton, M.J., Barton, T.J. & Shaw, R.D., 1991. The nature of faulting along the margins of the Fitzroy Trough, Canning Basin, and implications for the tectonic development of the trough. Exploration Geophysics, 22, 111–116.

Edwards, A.C., 1984. Progress report on Pb-isotope studies of the Lennard Shelf area, Western Australia. BHP internal report, CR 4122, 88 pp.

Etminan, H. & Hoffmann, C.F., 1989. Biomarkers in fluid inclusions: a new tool in constraining source régimes and its implications for the genesis of Mississippi Valley-type deposits. Geology, 17, 19–22.

George, A., Playford, P.E. & Powell, C.McA., 1995. Platform-margin collapse during Famennian reef evolution, Canning Basin, Western Australia. Geology, 23, 691–694.

Isles, D., Watt, M., Harman, P. & Lebel, A., 1987. Geophysical experience from the Blendevale deposit, WA. Exploration Geophysics, 18, 108–110.

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

Klopper, G., 1993. Characteristics and genesis of breccias in the lower dolomite unit, Cadjebut Zinc Mine, Lennard Shelf, W.A. B.Sc. Hons thesis, Curtin University of Technology, 98 pp. (unpublished).

Lambert, I.B. & Etminan, H., 1987. Biochemistry and origins of sediment-hosted base-metal sulphide deposits. BMR 87, Yearbook of the Bureau of Mineral Resources, Geology & Geophysics, Canberra, 89–93.

Leach, D.L. & Sangster, D.F., 1993. Mississippi Valley-type lead–zinc deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I. & Duke, I.M. (editors), Mineral deposit modelling. Geological Association of Canada, Special Paper 40, 289–314.

McCracken, S., 1994. Timing of hydrocarbon migration into the Admiral Bay Fault Zone, Canning Basin. In: Purcell, P.G. & Purcell, R.R. (editors), The sedimentary basins of Western Australia. Proceedings of Petroleum Exploration Society of Australia, Symposium, Perth, 739–753.

McManus, A. & Wallace, M.W., 1992. Age of Mississippi Valley-type sulfides determined using cathodoluminescence cement stratigraphy, Lennard Shelf, Canning Basin, Western Australia. Economic Geology, 87, 189–193.

Murphy, C.G., 1990. Lennard Shelf lead–zinc deposits. Australasian Institute of Mining and Metallurgy, Monograph 14, 1103–1109.

Oliver, J., 1986. Fluids expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena. Geology, 14, 99–102.

Playford, P.E., 1980. Devonian 'Great Barrier Reef' of the Canning Basin, Western Australia: The American Association of Petroleum Geologists, 64(6), 814–840.

Ringrose, C.R., 1989. Studies of selected carbonate-hosted lead–zinc deposits in the Kimberley region. Geological Survey of Western Australia, Perth, Report, 24, 103 pp.

Sangster, D.F., 1990. Mississippi Valley-type and sedex lead–zinc deposits: a comparative examination. Institution of Mining and Metallurgy, 99, sec. B, 21–42.

Sverjensky, D.A. & Garven, G., 1992. Tracing great fluid migration. Nature, 356, 481–82.

Tompkins, L.A., Rayner, M.J., Groves, D.I. & Roche, M.T., 1994a. Evaporites: in-situ sulfur source for rhythmically banded ore in the Cadjebut MVT Zn–Pb deposit, Western Australia. Economic Geology, 89, 467–492.

Tompkins, L.A., Pedone, V.A., Roche, M.T. & Groves, D.I., 1994b. The Cadjebut deposit as an example of MVT mineralization on the Lennard Shelf, Western Australia—single episode or multiple events? Economic Geology, 89, 450–466.

Vaasjoki, M. & Gulson, B.L., 1986. Carbonate-hosted base metal deposits: lead isotope data bearing on their genesis and exploration. Economic Geology, 81, 156–172.

Vearncombe, J.R., Dentith, M., Dörling, S., Reed, A., Cooper, R., Hart, J., Muhling, P., Windrim, D. & Woad, G., 1995. Regional and prospect-scale fault controls on Mississippi Valley-type Zn–Pb mineralization at Blendevale, Canning Basin, Western Australia. Economic Geology, 91, 181–186.

Received 1 February 1996; accepted 11 October 1996