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Conductivities of Broken Hill style lead ores

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Introduction

In terms of volume, the main conducting mineral in the Broken Hill (New South Wales) style of lead-zinc mineralisation is medium to coarse grained (~1 mm +/-) galena, PbS. The zinc mineral is an iron-rich sphalerite: marmatite (Zn, Fe)S. Sphalerite is a semiconductor with a wide band gap rendering it non-conductive (Shuey, 1975). To assess exploration in this important region, it is useful to have some information on the conductivity behaviour of these ores. Accordingly a suite of sixteen samples was examined – nine from lead mineralisation, and seven from zinc mineralisation. The results are referenced to the conductivities of three 'ideal', very high grade (collector grade), virtually pure, very coarse grained (>1 mm) galena from Rapid Bay (South Australia), Sweetwater Missouri (USA), and Dalnegorsk (far eastern Russia). The samples were sourced from dealers, the writer's collection, and some material from the AMIRA Project 369A (Emerson and Yang, 1994). The basic mineralogy is given in the notes to Table 1. Representative materials from some of the test samples are shown in Figure 1.

Besides the AMIRA results, some data on lead-zinc sulphide conductivities and resistivities have been published by Emerson (1997) and Bishop and Emerson (1999). The data presented herein supplements the previous work, but the emphasis is on galena; previously it was on the sphalerite.

'Broken Hill type' deposits comprise stratified lead, zinc and silver mineralisation in quartz-gahnite, garnet-quartz horizons (Stevens et al., 1990). Johnson and Klingner (1975) give a good outline of the Broken Hill mineralisation styles where lead and zinc lodes occur in a Proterozoic metasedimentary sequence subjected to granulite grade metamorphism.

In hand specimen, or under 20x binocular, galena is easily recognised by its lead-grey colour and streak, metallic lustre, perfect cubic cleavage, and softness (Moh's hardness 2 ½). Marmatite is harder, and readily identified by its dark grey blackish colour, subdued lustre, perfect [011] cleavage, and red-brown streak. Other sulphides (Table 1) were not regarded as being important, except for the yellowish sulphides, pyrrhotite and chalcopyrite. Galvanic microprobing permitted assessment of galena intra- and inter-grain electrical conductivity, and this was facilitated by the coarse grain sizes.

Foliation is discounted as a variable as none was obvious at core scale. The materials are regarded as quasi-random, coarse grained, aggregates of mainly galena and marmatite set in a silica/silicate variably grained host in which fine loops and threads of pyrrhotite and chalcopyrite can also occur. Given the high metamorphism to which the Broken Hill rocks were subject, it was not surprising to see that ductile, soft galena, apparently mobilised along grain boundaries, thus contributing to a more effective electrical framework. The galena grains in contact with one another appear to be well sutured.

For reference, nominal values of conductivity, magnetic susceptibility, and density have been ascribed, in Table 1 and Figure 3, to the minerals mentioned in this article. These values are based on data published by: Shuey (1975); Olhoeft (1981); Clark and Emerson (1991); Deer et al., (1992); Clark (1997); and Emerson et al., (2001).

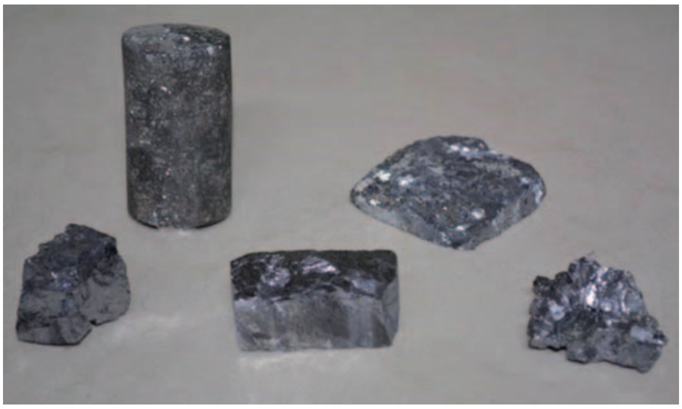

Figure 1. *This photograph shows subsamples representative of some of the cored galena materials. The first prism, on the left, is from Sweetwater, Missouri; it has 10 mm +/- grainsize and an EM conductivity of 7812 S/m. The second prism, in the middle, is from Rapid Bay South Australia; it has 5 mm +/- grainsize and conductivity of 6364 S/m. These two prisms are virtually pure galena continua. The third subsample of irregular outline on the right is from Dalnegorsk in Russia; it has 5 mm +/- grainsize but it contains some gangue, voids, and other discontinuities so its lower conductivity of 3010 S/m is not unexpected. The slab is from the parent lead lode material from which L10 was cored (see Table 1), it contains about 60% by volume of distributed galena with grainsize 2 mm +/-; L10's conductivity is 587 S/m. The 45 mm diameter core is Z3 from the zinc lode suite with 70% marmatite, 15% galena, and small percentages of pyrrhotite/chalcopyrite that have contributed to Z3's conductivity of 87 S/m. In the photo the galena, or at least some of it, can be identified by the metallic reflections, but the wispy pyrrhotite and chalcopyrite in Z3 cannot be seen at this scale.*

Measurements

Laboratory mesoscale measurements were carried out on cored, air-dried, low porosity samples for electrical conductivity and magnetic susceptibility, to 1% accuracy. Induction coils (Figure 2) were used and energised to 1 MHz for induced electromagnetic conductivity and 400 Hz for magnetic susceptibility. Changes in the resistance (R) and inductance (L), when cores were inserted, were measured by an impedance bridge. Following the Yang and Emerson (1997) procedures, conductivity was determined from ΔR, and susceptibility from ΔL. Volumes for the densities were measured by mensuration or by Archimedes' immersion.

Figure 2. *This photograph shows an induction coil of the type used in the measurements. It is 95 mm long x 50 mm internal diameter; the cylindrical housing is 120 mm long. At a particular frequency (below the onset of the skin effect) the change in resistance (ΔR) and in inductance (ΔL) are measured on an impedance bridge when a core is inserted. From these quantities, conductivity (ΔR) and magnetic susceptibility (ΔL) are calculated (see Yang and Emerson, 1997).*

Although the writer has carried out many galvanic measurements on samples from the Broken Hill Block, EM conductivity was the preferred technique in this exercise. The EM measurement is not responsive to insulating minerals, it just 'sees' conductors and induces eddy currents in them; also it is quicker to do. Lab EM favours conductive features normal to the core axis; galvanics, parallel to the core axis. The differences, which do exist for Broken Hill mineralisation, are related to texture and will not be dealt with here (see AMIRA Report P369A).

Galvanic microprobing of sulphides was undertaken by measuring DC ohmic resistance using two electrode needle probes. This gave a qualitative and relative indication of sulphide conductivities. In four electrode measurements, described by Harvey (1928), a Wenner micro-array was set on polished mineragraphic blocks to give quantitative grain resistivity/conductivity values. Such measurements were beyond the scope of this article.

Results

The data cited in Table 1 are categorised into five groups for which conductivities have been plotted against density in

Table 1. Physical properties of some coarse grained semi-massive to massive galena ores

Sample	Plot code	Bulk density (g/cc)	% gal	% sph [marm.]	% s	% gangue	EM cond (S/m)	mag k (SI × 10^{-5})
Very high grade galena								
C1 [RB]	▲	7.56	100	→0	→0	→0	6364	All
C2 [SM]		7.45	99	→0	→0	1	7812	diamagnetic
C3 [RUS]		7.07	90	→0	→0	10	3010	(negative)
Broken Hill lead lode galena with networked pyrrhotite (po) and chalcopyrite (cpy)								
L1 [US79]	◆	4.93	40	→0	5	55	3750	241
Broken Hill lead lode, relatively poor intra and intergrain elec. conductivity, low sph, no po/cpy								
L2 [B Pr]	■	5.40	55	5	→0	40	167	25
L3 [A Pr]		6.43	75	5	→0	20	500	38
Broken Hill lead lode, good intra and intergrain elec. conductivity, low sph, no po/cpy								
L4 [B1]	●	4.61	35	5	→0	60	347	36
L5 [B2b]		4.49	30	5	→0	65	269	43
L6 [B2f]		3.97	20	5	→0	75	135	40
L7 [B3]		6.08	66	2	→0	32	680	37
L8 [B9]		6.21	70	2	→0	28	778	38
L9 [B8]		6.65	80	2	→0	18	842	40
L10 [B7]		5.67	58	2	→0	40	587	41
Broken Hill zinc lode sph and gal, with networked po, cpy								
Z1 [AM10]	+	4.94	35	35	2	28	1700	210
Z2 [AM9]		4.76	25	65	2	8	780	276
Z3 [AM7]		4.37	15	70	≥1	≤14	87	228
Z4 [AM8]		4.18	10	75	≥1	≤14	5	232
Z5 [AM1]		3.87	0	90	≥1	≤9	1	244

Notes:
1. Mineralogy estimated visually under binocular microscope, volume percentages regard as approximate, s = po, cpy.
2. Broken Hill sulphide minerals include: economic targets galena, PbS, 7.5 - 7.6 g/cc, diamag.; 'black jack' sphalerite [marmatite (Zn, Fe)S ≥ 10% Fe content], 4.00 g/cc (varies with Fe), pure sphal is an insulator & diamag. but marmatite is a paramagnetic with mag k ~ 100 x 10^{-5} (varies with Fe). Also accessories: pyrrhotite, Fe_7S_8, 4.6 g/cc which may be both monoclinic, mag k ~ 40 000 x 10^{-5} SI, and hexagonal, mag k ~ 150x10^{-5} SI; and others in trace amounts, such as loellingite, $FeAs_2$, arsenopyrite, FeAsS; tetrahedrite, complex silver sulphide.
3. Broken Hill gangue minerals include: Mn garnet, spessartine, 4.18 g/cc, 680 x 10^{-5} SI, mag k; Mn silicate, rhodonite, 3.69 g/cc, 415 x 10^{-5} SI; quartz 2.65 g/cc, diamagnetic (negative mag k); calcite, 2.72 g/cc, diamag; Zn aluminate, gahnite, 4.55 g/cc, diamag; and others.

Figure 3, to view features and trends in perspective. Magnetic susceptibilities have not been used in a plot as the pyrrhotite is a mix of monoclinic and hexagonal types, and the magnetic susceptibilities of marmatitic sphalerite and some of the gangue minerals, e.g. garnet and rhodonite, are not trivial. Sulphide electrical grain-quality values are given in Table 2: the lower the ohmic resistance, the better the grain quality, singly and in aggregate.

The reference group C of very high grade, very coarse grained, very dense, diamagnetic galenas, have excellent conductivities, ranging from 3010 to 7812 S/m. The conductivities increase with density towards the nominal galena value of 10 000 S/m.

The galena ore L1, with pyrrhotite and chalcopyrite, has a markedly lower density (it has less than half the galena content of group C), but has a conductivity that is comparable with group C.

Samples L2 and L3 were galvanically microprobed to ascertain why the conductivities of those galena-rich samples were only fair, 167 and 500 S/m. The inter- and intra-grain electrical continuities, while extant, were found to be inferior to those of the next group, samples L4 to L9, and so plot beneath them in Figure 3.

In Figure 3, group L4-L9 has a moderate rise in conductivity (135 to 842 S/m) over a wide range of density (3.97 to 6.65 g/cc) as the galena conductivity framework increases in volume. In the writer's experience, these good, but not excellent, conductivities are typical of granular galena in a metamorphic setting. Extrapolated to galena's density it seems that about 1000 S/m could be the limiting conductivity for very massive galena of this type. Galvanic microprobing indicated that electrical continuity of the galena was inferior to group C.

The zinc mineralisation group, Z1 to Z5, with ancillary galena and pyrrhotite, manifests an extraordinary increase in conductivity, 1 to 1700 S/m, over a narrow density range, 3.87 to 4.94 g/cc. This is a consequence of the pyrrhotite and chalcopyrite operating an independent filamentary network through the galena, sphalerite, and gangue grains. While galena without doubt contributes to the conductivity (except for Z5 where it is absent) the conductivity character is dominated by the yellow sulphides, pyrrhotite and chalcopyrite. Galvanic microprobing indicates that their continuity is better than all the others, despite the fine, thready nature of these two sulphides.

Table 2. Sulphide grain relative electrical continuity

Category	Intra-grain (ohms)	Inter-grain (ohms)
C1–C3		
Collector grade galena		
Very coarse grain size	10	15
L1		
Lead lode + yellow sulphide		
Galena	50	200
po/cpy	<1	1
L2, L3		
Lead lode		
Galena	100	300
L4–L10		
Lead lode		
Galena	30	50
Z1–Z5		
Lead lode		
Galena	40	80
po/cpy	2	20

Note: Ohms measured by two electrode needle probes connected to a DC voltage source; intra-grain electrode spacing 1 mm, inter-grain spacing several mm to cm; measurements included contact resistance between probe and sulphide so regard data as qualitative and relative indications of electrical grain quality, only; typical values cited.

Discussion

Galena's conductivity is quite variable. Studies of crystals have shown both *n*-type and *p*-type semi-conduction and conductivities ranging from 1 to 100 000 S/m with *p*-type more resistive than the *n*-type by an order of magnitude (Shuey, 1975, see his histogram fig. 13-1). Considering the available data in the literature, a range of around 1000 to 10 000 S/m for galena crystals seems reasonable.

Aggregates of crystals are a different matter. The cubic crystals' grain boundary characteristics (thin films of other mineral phases, voids, microcracks, cleavage) usually result in aggregated galena

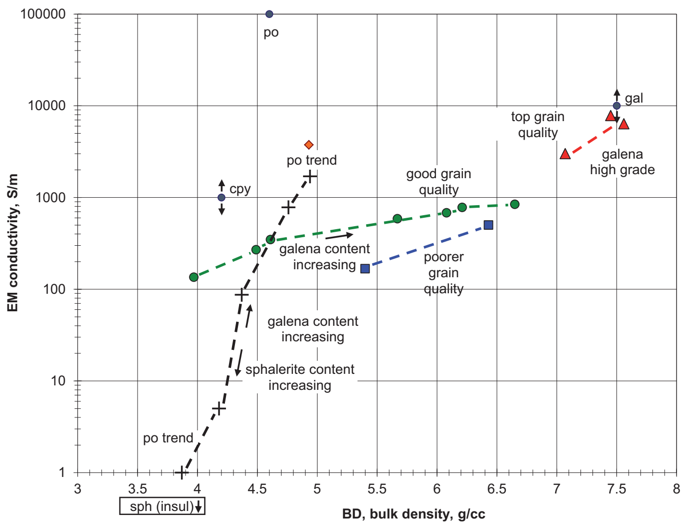

Figure 3. *A plot of electromagnetic (induced) conductivity against density, in the air-dried state, for three types of coarse grained (1 mm +/-) galena ores. Four trends are shown: the very high grade, very dense, very coarse grained samples plot near galena's nominal conductivity value and have excellent conductivity; the galena-dominant lead lode values show fair (at lower density) to good (at higher density) conductivity tending to, by extrapolation, a value of about 1000 S/m at galena's density. Two samples show subdued conductivity as a consequence of poorer galena grain electrical quality and grain continuity. The pyrrhotite trend for the Pb-Zn ore shows very good conductivity as density increases and this is ascribed to pyrrhotite, and perhaps chalcopyrite, electrically pervasive minerals even at low concentrations, significantly boosting any galena framework conductivity or providing a sparse but effective filamentary conduction when galena is low or absent. A high conductivity interpreted from a geophysical survey, in the absence of other data (e.g. gravity), cannot be inferred to indicate high grade galena in Broken Hill type lead-zinc provinces if there is pyhrrhotite about. Reference mineral conductivities plotted on this graph (as blue dots) are approximate.*

having a conductivity diminished by an order of magnitude, or more, below the single crystal values (Parkhomenko, 1967; Shuey, 1975). However, in exceptional conditions, when tectonic stress imparts better suturing of grain contacts, and strain effects cause plastic deformation flowage of galena, the results are good grain linkages and the formation of an effective electrical framework throughout the ore as is the case here for galena volume contents of 20% and above. The 'percolation' threshold for galena in the Broken Hill styles of mineralisation could be of the order of 15%, but this aspect is not pursued here.

In contrast to cubic galena with its blocky habit, monoclinic / hexagonal pyrrhotite and tetragonal chalcopyrite tend to be dendritic and interconnected (Shuey, 1975) forming loops, linears or networks, thus boosting conductivity even in small amounts, as in L1.The very high-grade reference group C galena, with fewer discontinuities, has very good grain conductivity. The grains are very large (5 mm +) and well linked, so these massive materials function, more or less, as electrical continua with excellent mesoscale conductivity tending towards a notional galena value of 10 000 S/m.

The lead mineralisation group, L4 to L9, has galena grains with internally developed cleavage planes but still manifests good grain conductivity and good grain linkages. Conductivity gradually increases with density and could, by extrapolation, peak at around 1000 S/m for 100% galena.

The lead mineralisation group, L2 and L3, has galena grains that are of a quality inferior to the previous group and so these two samples plot below the main galena trend.

The pyrrhotitic lead ore L1 with a galena content of 40%, has a high conductivity of 3750 S/m as a consequence of its excellent network of yellow sulphides. This sample could be compared with L4: 35% galena, no pyrrhotite, 347 S/m.

The zinc mineralisation group (Z1 to Z5) has subordinate or vanishing galena content which does contribute to conduction, but this is minor compared to the contribution from the contained yellow sulphide network. This boosts conductivities from low but finite levels (1 S/m for 90% sphalerite, Z5) through to the very good conductivity at the highest density 4.94 g/cc (1700 S/m, Z1, 35% galena, 35% sphalerite), approaching L1.

It is noted that pyrrhotitic L1 and Z1 to Z5 have magnetic susceptibilities higher (~240 x 10^{-5} SI) than the galena groups L2 to L9 (~40 x 10^{-5} SI) but no analysis has been attempted in the absence of better mineralogical information.

Conclusions

These limited test results for Broken Hill style semi-massive to massive lead mineralisation suggest that, after enduring granulite metamorphism, high grade galena ores, with densities exceeding 6.6 g/cc, can exhibit good conductivities, ≤1000 S/m, as a result of the galena's grain quality factors including grain conductivity, grain suturing, and grain linkages. However, these conductivities can be exceeded in lower grade galena and even sphalerite ore when a small, but electrically very effective, pyrrhotite and chalcopyrite content is networked through the rock.

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References

Bishop, J. R., and Emerson, D. W., 1999, Geophysical properties of zinc-bearing deposits: *Australian Journal of Earth Sciences*, **46**, 311–328. doi:10.1046/j.1440-0952.1999.00706.x

Clark, D. A., 1997, Magnetic petrophysics and magnetic petrology – aids to geological interpretation of magnetic surveys: *AGSO Journal of Australian Geology & Geophysics*, **17**, 83–103.

Clark, D. A., and Emerson, D. W., 1991, Notes on rock magnetization characteristics in applied geophysical studies: *Exploration Geophysics*, **22**, 547–555. doi:10.1071/EG991547

Deer, W. A., Howie, R. A., and Zussman, J., 1992, *An introduction to rock forming minerals*: Longman Scientific & Technical.

Emerson, D. W., 1997, Insights from laboratory mass property crossplots: *Preview*, **70**, 10–14.

Emerson, D. W., and Yang, Y. P., 1994, The electromagnetic conducting properties of some sulphide rocks and ores: *Australian Mineral Industries Research Assoc. Report P369A*. AMIRA Melbourne.

Emerson, D. W., Williams, P. K., and Luitjens, S., 2001, The conductivities of komatiitic nickel ores at Kambala W.A.: *Preview*, **92**, 38–41.

Harvey, R. D., 1928, Electrical conductivity and polished mineral surfaces: *Economic Geology and the Bulletin of the Society of Economic Geologists*, **23**, 778–803. doi:10.2113/gsecongeo.23.7.778

Johnson, I. R., and Klingner, G. D., 1975, The Broken Hill ore deposit and its environment, in: *Economic Geology of Australia and Papua New Guinea, Vol. 1 Metals*, ed. Knight, C. L., pp. 476-491. The Australasian Institute of Mining and Metallurgy, Melbourne.

Olhoeft, G. R., 1981, Electrical properties of rocks, in: *Physical properties of rocks and minerals*, Vol. 11-2, eds Touloukian, Y.S. et al., ch. 9, 257–329: McGraw Hill.

Parkhomenko, E. I., 1967, *Electrical properties of rocks*: Plenum Press.

Shuey, R.T., 1975, *Semiconducting ore minerals*: Elsevier Sci. Publ. Coy.

Stevens, B. P. J., Barnes, R. G., and Forbes, B. G., 1990, Willyama Block – regional geology and minor mineralisation, in: *Geology of the Mineral Deposits of Australia and Papua New Guinea*, ed. Hughes, F. E., pp. 1065–1072. The Australasian Institute of Mining and Metallurgy, Melbourne.

Yang, Y. P., and Emerson, D. W., 1997, Electromagnetic conductivities of rock cores, theory and analog results: *Geophysics*, **62**, 1779–1793. doi:10.1190/1.1444278

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