ZONING AND GENESIS OF THE ORES

The term "zoning", when applied to mineral deposits, is normally used in a purely descriptive sense to imply the existence of successive belts or layers of differing mineral content, without implication of the cause of the zoning. The zoning may refer to variations within a single vein, or may refer to variations on a district- or regional-scale.

Although zoned deposits are often spatially related to igneous centres, this is not a prerequisite for classification of deposits as zoned. Zoning may be recognized where there is no obvious relationship to an igneous source, and syngenetic as well as hypogene zoning has been reported (e.g. Amstutz, 1959).

The zonal theory of ore deposits was first formulated by Spurr (1907) and was more fully developed by Emmons (1936, 1940). In a review article, Park (1955) stated that while the existence of compositional zoning is to be regarded as a fact, the causes of zoning are not clearly understood. More recently, attempts have been made (Parker, 1962; Barnes, 1962) to use the methods of physical chemistry in a more quantitative approach to the problem of zoning.

Zoned mineral deposits have been described from many countries but possibly the best known deposits showing zoning are those of Cornwall (England), Butte (Montana) and Bingham (Utah). Recent investigations into zoned deposits have been published by Sims and Barton (1962 - Central City

District, Colorado), Petersen (1965 - Central Peru) and Hawley (1965 - Sudbury, Ontario).

The mineralogical zoning of the ores in the Zeehan field was first recognized by Waller (1904) and was later described more fully by Twelvetrees and Ward (1909, 1910) and Ward (1911). These authors postulated three zones located around the south-east border of the Heemskirk Granite, with one of the zones sub-divided into two belts, as follows.

(1) Tin zone

(2) Contact-metamorphic zone

(3) Trans-metamorphic zone

(a) Pyritic belt.

(b) Siderite belt.

The tin zone consisted of the cassiterite-bearing veins within the borders of the Heemskirk Granite. The contact-metamorphic zone represented the contact aureole of the granite, and the trans-metamorphic zone covered the area between Comstock and Zeehan.

In addition to the zones, Twelvetrees and Ward (1909, 1910) recognized nine "vein-types", based upon the major components of the ore-bodies in the Zeehan field (not including the cassiterite ores within the Heemskirk Granite). The vein-types and the main occurrences given by Twelvetrees and Ward are as follows:-

(1) Pyrite-cassiterite.

Noted by Twelvetrees and Ward in one occurrence only, viz. a small vein on Oonah Hill, near the Oonah Mine.

(2) Magnetite

Tenth Legion and other magnetite deposits in Comstock area.

(3) Magnetite-sphalerite-galena-chalcopyrite-pyrite.

Silver Stream workings.

(4) Pyrite-sphalerite-galena

Western part of the Zeehan field, particularly in Comstock area.

(5) Pyrite-galena

Found mainly in the western part of the field and merging into pyrite-sphalerite-galena ores.

(6) Siderite-galena

Occurs in central and eastern part of the field.

(7) Nickel-silver

One occurrence only, viz. Central Balstrup Mine.

(8) Pyrite-stannite-chalcopyrite

Oonah Mine and Clarke's Lode in the Zeehan Queen workings.

(9) Pyrite-stannite-galena

Twelvetrees and Ward include this type as a slightly different version of type 8, and state that this type occurs in parts of Clarke's Lode and in the deeper workings of the Oonah Mine.

Twelvetrees and Ward (1909, p.13) observed "that there is a well-defined succession of vein-types ..... on passing outwards from the granite massif of Heemskirk". The following extract from Ward (1911, p.153) summarized the more detailed description of the zoning by Twelvetrees and Ward (1910).

"The tin-bearing lodes of the Heemskirk district exhibit some variety of composition. They are marked in almost every case by the presence of small amounts of bismuthinite, molybdenite and wolframite with the cassiterite. Of the gangue minerals, tourmaline is the most characteristic and widely distributed. Fluorite is not abundant.

Lying to the eastward (and southward) of this area, in which cassiterite is the most constant metallic mineral, are the magnetic masses of the Comstock district. The magnetite is found in very large bodies which are seldom free from admixture with other metallic minerals. Although often nearly perfectly pure, the magnetite is found associated with galena, blende, chalcopyrite and pyrite, and one instance is known* in which cassiterite accompanies it.

Still further to the eastward lie the large pyritic lodes of the western portion of the Zeehan field. Pyrite is the most abundant mineral, and blende and galena are associated with it. At one point** there is a notable development of stannite, with which are associated pyrite, chalcopyrite, galena, bismuthinite, wolframite, tetrahedrite, siderite, and sporadic traces of fluorite.

The eastern limit of the area under consideration - the Zeehan field proper - is characterized by lodes of which a considerable portion consists of siderite, with which are found galena, blende, and smaller quantities of tetrahedrite and chalcopyrite.

Between these broad groups lie many associations which clearly mark transitional stages. Certain metals have been proved to exist in almost every type ....

The gangue minerals in the lodes are also found to transgress the limits of the main groups referred to above."

* St. Dizier Mine in North Heemskirk area.

** Oonah mine.

Figure 10 (adapted from Twelvetrees and Ward, 1910, by Hall and Solomon, 1962) demonstrates the zonal arrangement proposed by Twelvetrees and Ward.

Twelvetrees and Ward regarded the tin ores of the Heemskirk field, the magnetite ores of the Comstock area, and the sulphide ores of the Zeehan field as being derived from a single source during a single phase of mineralization. The basic intrusive rocks occurring in the Comstock area, and elsewhere around the margin of the Heemskirk Granite, were considered to have been intruded a short time before the granite, but the two magmas were regarded as the result of differentiation from a common magma.

According to Twelvetrees and Ward, the ores were deposited from solutions emanating from the granite; fracture planes and fault zones became suitable loci for deposition of the ores. A temperature gradient outwards from the granite was postulated as the overall controlling factor which resulted in the mineralogical zoning.

Twelvetrees and Ward regarded the stannite ores as a possible exception to the hypothesis of a single phase of mineralization, and stated that (1910, p.68) "it appears probable that the stannite-bearing lodes have been deposited from solutions which have brought upwards an assemblage of metals distinct in many respects from that which migrated in the solutions whibh deposited the galena-bearing series of vein-types..........".

Summary descriptions of the zoning have been provided in recent years by Edwards (1953) and McAndrew (1965), who have accepted the zonal hypothesis of Twelvetrees and Ward. The Zeehan mineral deposits have also been quoted by Park

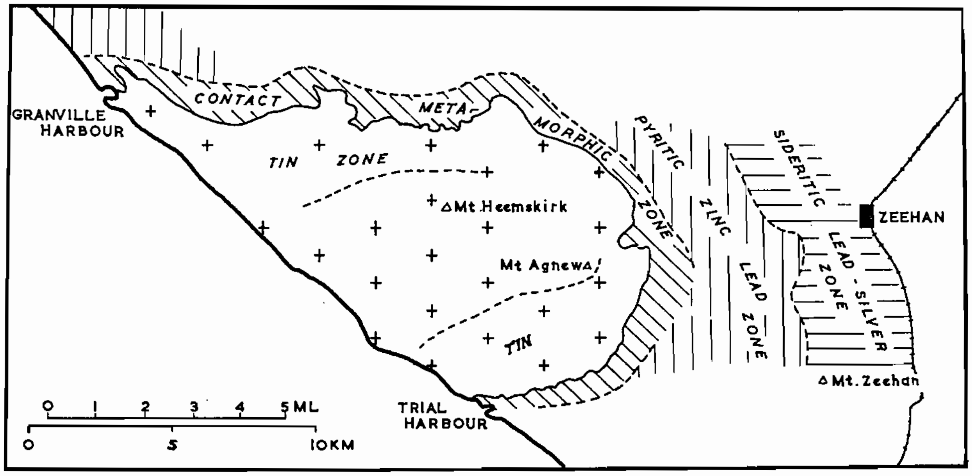

FIGURE 10. Ore zones around the Heemskirk Granite. (From Hall and Solomon, 1962, adapted from Twelvetrees and Ward, 1910).

(1955) and Bateman (1956) as classic examples of zoned ore deposits.

In recent years some doubts have been expressed about the validity of the zoning of the Zeehan ores and about the relationship of the ores to the granite. The discovery that the Tenth Legion magnetite deposits were derived from Cambrian basic rocks (Hughes, 1958; Blissett, 1962) cast doubts on the "contact metamorphic" zone of Twelvetrees and Ward, and this led to doubts on the remaining zones.

Hall and Solomon (1962) pointed to the lack of detailed mineralogical descriptions and suggested that the zoning could be fallacious. Solomon (1965, p.476) has noted that if the Zeehan field is considered with the Dundas, Renison Bell, Rosebery, Williamsford and Tullah deposits, these occupy a "narrow, north-east trending mineralized zone that contains all the important lead-zinc mineralization in Tasmania". Solomon also noted that this zone contains three centres of tin mineralization (viz. Renison Bell, Montana and Razorback, in the North Dundas and Dundas area) and suggested that the lead-zinc fields may represent lower-temperature haloes around the higher-temperature centres of tin mineralization.

King (1961) estimated that 85% of the production of lead ore from the Zeehan field came from mines located in upper Precambrian or early Cambrian rocks with associated spilites. Since these spilites are thought to belong to the same phase of vulcanism as the Mount Read Volcanics (Solomon, 1965), King's observation could be regarded as evidence for an exhalative origin for the Zeehan sulphide ores.

This relationship between ore and spilite may be fortuitous or may be due to the presence of dolomite which is associated with the spilite (see p.16). It is possible that the dolomite has, to some extent, caused a localization of ore deposition. This relationship between a carbonate horizon and ore has been noted elsewhere in western Tasmania (Hall and Solomon, 1962) and is discussed further below (p.304).

The mineralogical study by this author has provided evidence in support of the main ideas expressed by Twelvetrees and Ward. The sulphide ores of the Zeehan field do show a variation in mineralogy which is zonal with respect to the geographic position of the Heemskirk Granite.

The main weakness, in the light of present information, in the scheme presented by Twelvetrees and Ward concerns the "contact metamorphic" zone. The major components assigned to this zone were the Tenth Legion magnetite deposits, and the ores of the Silver Stream Mine. Twelvetrees and Ward observed that the Tenth Legion deposits consisted almost entirely of magnetite with only traces of pyrite, sphalerite and galena, whereas the Silver Stream ore contained sphalerite, chalcopyrite, pyrite and galena with minor magnetite. This observation formed the basis of the proposed gradation between the magnetite deposits and the sulphide ores.

Although it is now accepted that the Tenth Legion magnetite deposits are not related to the sulphide ores, this does not necessarily invalidate the remainder of the zonal theory.

Small amounts of magnetite were recorded in the sulphide ores in the Silver Stream workings (Waller, 1903; Twelvetrees and Ward, 1910). Unfortunately, adequate samples are lacking from this important locality, but the material studied did confirm the presence of magnetite. A sample consisting largely of sphalerite, chalcopyrite and pyrite (P.216) contained a minor amount of magnetite as inclusions within the sphalerite. It would, therefore, appear that the magnetite occurring in the sulphide mineral assemblages of the Silver Stream ore is not directly related to the magnetite deposits in the Comstock area.

Although the latter bodies are considered to represent magnetite which segregated from basic intrusive bodies, it is likely that concentration of the magnetite was brought about by contact metamorphism. Waller (1904, p.22) noted that the magnetite bodies were confined to "the country immediately surrounding the Heemskirk Granite...", and Blake (1940) reported the bodies to be short and narrow lenses within serpentine and calc-silicate material. The occurrence of the magnetite bodies is apparently restricted to the contact metamorphic aureole of the granite, and this suggests that contact metamorphism caused a redistribution of disseminated magnetite into the massive bodies.

Twelvetrees and Ward (1910, p.49) and Ward (1911, p.153) mention cassiterite as having been found in one formation of magnetite. This refers to reports by Waller (1902a, 1903) of cassiterite occurring in "irregular veinlets and grains in a magnetite silicate rock" at the St. Dizier Mine, which is located a short distance north of the northern margin of the Heemskirk Granite, approximately 5½ miles east-south-east from Granville Harbour and 3 miles north-west of Mt. Heemskirk. There is not enough information on this association for definite suggestions to be made on the genesis of the minerals conserned, but it appears likely that this represents an overlap of two different periods of mineralization. From Waller's description it would appear that the magnetite is associated with altered Cambrian basic or ultrabasic rocks, and it is likely that the cassiterite was related to the nearby Devonian granite.

The description of the mineralogy of the individual mines, and the summaries of the distribution of the various ore and gangue minerals, demonstrate that there is a considerable mineralogical variation throughout the Zeehan field. An analysis of these mineralogical descriptions shows several well-defined trends in the variation, and the overall pattern is one which is in essential agreement with the zonal pattern of Twelvetrees and Ward.

The most obvious feature of the overall mineralogy of the field is a general decrease from west to east in the ratio (pyrite + sphalerite): (galena + siderite). The ores of the Comstock part of the field are predominantly pyrite and sphalerite with galena less abundant. Quartz is the dominant non-metallic mineral in these ores. The composition undergoes a change to the east; the abundances of pyrite and sphalerite decrease while the galena and siderite contents increase. The ores in the mines in the eastern part of the field consist largely of galena and siderite, with pyrite, sphalerite and quartz as minor constituents. Between these extremes are ores of intermediate composition.

The distribution of the antimony-bearing sulphides, boulangerite and bournonite, can also be related to the zonal arrangement of the ores. Since the boulangerite and bournonite commonly occur in association with galena, it follows that these minerals are more common in the east than in the west. But the abundance is apparently greatest in a comparatively narrow belt extending from the Swansea Mine, in the south, to Queen Hill in the north. Bournonite is particularly common at the Swansea and Grubb's mines; boulangerite is abundant at the Spray Mine and common in many others in this belt.

Twelvetrees and Ward (1910) noted that the silver content of the galena increased to the east. This observation is, in general, substantiated by reported silver assays and production figures, and also by the abundance of silver-bearing minerals (particularly tetrahedrite) associated with the galena in polished sections. As discussed earlier, however, (see p.206) this is a generalized pattern to which there are local exceptions.

The iron content of the sphalerite also shows a variation which appears to correspond approximately to the zonal pattern. The composition of the sphalerite has been discussed in some detail in a previous section and the iron contents are shown in Figure 4.

The abundance in the sphalerite of pyrrhotite and chalcopyrite exsolution bodies also show a marked decrease from west to east. The pyrrhotite bodies are present only in the iron-rich sphalerite in the western part of the field. Chalcopyrite bodies are more abundant in the iron-rich sphalerite, but are still present in most samples of sphalerite in the east.

Arsenopyrite is a minor constituent of many of the pyritic ores and is, therefore, more common in the western part of the field. Arsenopyrite is, however, rare in the samples examined from the Silver Stream and Comstock Mines, and the most common occurrences are in the western to central part of the field (Sylvester, Britannia and Spray Mines).

The zoning is also accompanied by an increase in the cation:anion ratio in the major constituents. e.g.

Pyrite	Fe:46.6	S:53.4
Sphalerite	Zn:67	S:33
Galena	Pb86.6	S13.4

It should be stressed that the general pattern of variation in mineralogy is one varying abundances. The most common constituents are present throughout the field, and it is the proportions of the minerals which show the variation.

Significant exceptions to this overall pattern are found in the Oonah Hill - Queen Hill locality and at the Central Balstrup Mine in Austral Valley.

The ores found in the Oonah Mine and in some of the Queen Hill workings do not conform to the pattern outlined above. To the north and south of these workings there are the "normal" siderite-galena ores, but the ore from the Oonah Mine is rich in pyrite and stannite with significant cassiterite also present. A similar assemblage is found in Clarke's Lode, on Queen Hill, and ore from the Stormsdown Mine, on Queen Hill, is largely pyrite with minor cassiterite.

Associated with the pyrite-stannite ore are other minerals rare or absent elsewhere in the field, viz. wolframite, bismuthinite and fluorite.

The assemblages in these ores are characteristic of higher temperatures of formation than the minerals in the nearby siderite-galena ores. Although Twelvetrees and Ward extended the eastern limit of their "pyritic belt" to include these ores, they realized that the occurrence was not explained satisfactorily by the concept of decreasing temperature outward from the granite. As outlined above (p.285) Twelvetrees and Ward suggested the possibility of the stannite-bearing lodes having been formed from solutions migrating upwards and introducing a distinct assemblage of minerals, but these were still regarded as having some relationship to the main ore-forming solutions.

This introduces the question of a third-dimension in the zoning. Although Twelvetrees and Ward described only a horizontal zoning, they did predict the presence of similar zones in the vertical plane. With the samples available for the present study it is not possible to determine the presence or absence of any vertical zoning, but the reports of Waller (1904) and Twelvetrees and Ward (1910) do contain observations which indicate some variation in mineralogy with depth. The siderite-galena lodes of the Zeehan Queen and Zeehan-Western mines apparently became more pyritic at depth. Pyrite was also more abundant in the lower levels of the Spray Mine, whereas the silver and antimony contents of the ore were higher in the upper levels. Ore from the Grubb's Mine was reported to show an increase in the sphalerite: galena ratio with depth.

This information is rather sketchy but does suggest that some vertical zoning was present. The possibility arises that the unusual mineralogy of ore from Oonah Mine, Stormsdown Mine, and Clarke's Lode may be due, at least in part, to a vertical zoning effect, which is superimposed upon the more obvious horizontal zoning. If the ore-forming fluids migrated upwards and outwards from the magmatic source, then the variation in mineralogy in this particular locality within the field may have been due to more favourable channels, or conduits, for the fluids which deposited the pyrite-stannite-cassiterite ores. It is also possible that this feature of the zonal pattern was related to a cupola-type of development of the granite in relation to this part of the field (see Figure 11).

The nickel ore of the Central Balstrup Mine, represents the other significant departure from the overall zoning pattern. This ore-body is the only occurrence in the Zeehan field of nickel minerals associated with the sulphide ores, the body being located in the "siderite belt" of Twelvetrees and Ward.

Williams (1958) suggested that this nickel might represent a partial remobilization of Cambrian nickel mineralization during the formation of the Devonian sulphide ores. The presence of nickel mineralization associated with

Cambrian basic intrusive rocks in Western Tasmania is well known (Williams, op.cit.) and several examples are found near the Zeehan field , e.g. Trial Harbour and Cuni. Reid (1922) reported the presence of small quantities of nickel minerals in a pyroxenite dyke near the Swansea Mine, and the map accompanying the report by Waller (1904) showed an occurrence of "nickeliferous pyrite" in a serpentine dyke along the Comstock tram, west of the Spray Mine. In view of the isolated nature of the nickel minerals in association with the Zeehan sulphide ores, as compared with the widespread distribution of Cambrian nickel mineralization, the suggestion by Williams is considered to be the most reasonable explanation that can be made at present.

A detailed mineralogical study has, then, provided evidence in support of the main proposal of Twelvetrees and Ward, viz. that the ores of the Zeehan field show a zonal pattern around the south-east margin of the Heemskirk Granite. One point of Twelvetrees and Ward which is not accepted is the supposed relationship between the magnetite deposits of the Comstock area (including the Tenth Legion deposit) and the minor amounts of magnetite associated with the sulphide ores. The zoning pattern, showing a geographic relationship to the Heemskirk Granite, points to the granite as having been the source of the ore-forming fluids.

In preference to the terminology of Twelvetrees and Ward, who proposed three zones with a subdivision into two belts of the third zone (see p.282, and Figure 10) the author

FIGURE 11. Geological section from Heemskirk Granite to Mount Dundas, showing distribution of zones in Zeehan mineral field and possible development of granite cupolas below Zeehan and Dundas fields. (Section based on Blissett 1962)

prefers the following divisions.

(1) Tin zone (within the granite)

(2) Pyritic zone

(3) Sideritic zone

The distribution of the zones is shown diagrammatically in Figure 11, which consists of a cross-section from the Heemskirk Granite to Mount Dundas.

An examination of the mineralogical data on the Zeehan ores reveals the following features which are considered to be significant concerning the origin of the ores.

(1) The zoning is apparently independent of rock-types or stratigraphic units.

(2) There is a close correlation between the observed paragenetic sequence and the zonal pattern.

(3) The zonal arrangement has an approximate relationship with the variation in iron content of sphalerite.

As noted above (p.287), there is a relationship between the distribution of spilite and ore, but the zonal pattern of the ores does not appear to be related to rock-types.

The paragenetic sequence and the sequence of minerals in the zonal pattern are clearly related, suggesting that paragenesis and zoning are, to a large extent, controlled by the same factors. Park(1955) has shown the similarity of the paragenetic and zonal sequences in other ore deposits.

The order in which minerals appear in a zonal sequence is possibly a more faithful record of the sequence of formation than is a paragenetic sequence.

In a zonal pattern, the sequence is recognized by changes in the actual composition of the ore between zones,ie. by the appearance of minerals and by changes in the relative proportions of the minerals. The recognition of a paragenetic sequence, however, depends largely upon the interpretation of the textures observed in polished sections of the ores, and, as discussed earlier, these textures are often ambiguous and many may be unreliable criteria of the order of crystallization.

The relationship between the zonal arrangement of the ores and the variation in iron content of sphalerite suggests a temperature control over the zoning. The overall pattern of variation of the iron in sphalerite has been discussed in an earlier section. Although the results could not be interpreted conclusively, it was suggested that these variations were controlled by a temperature gradient outfrom the granite, and by a corresponding decrease in activity of sulphur.

It is reasonable to assume that a temperature gradient was supplied by the granite, and that this gradient was an important factor in the control of the zonal pattern. Barton and Toulmin (1961) and Parker (1962) have demonstrated that sulphide deposition is an exothermic reaction which takes place along a negative temperature gradient. According to Parker, zoned deposits are more likely to result if the temperature gradient is steep, but it is not clear from Parker's data just what constitutes a steep gradient . The available temperature data on the Zeehan ores suggests that the temperature gradient was of the order of 2°C per 100ft. out from the granite.

Parker (op. cit) has also suggested that solutions are more important than gases in the transport of metals, and thermodynamic calculations by Barnes (1962) indicate that, to account for the commonly observed zonal sequences, it is necessary to assume transport of the metals as covalent-bonded complex ions.

COMPARISON WITH OTHER ZONED MINERAL DEPOSITS.

A survey of the literature on zoned deposits has failed to reveal any other mineral field which can be considered to be directly analogous to the ores of the Heemskirk-Zeehan field. Nevertheless certain similarites are apparent, and the zonal sequence of minerals observed in the Heemskirk - Zeehan ores is comparable with sequences described elsewhere.

The most obvious feature which emerges from a comparison with other zoned deposits is the weakness of copper mineralization in the Zeehan field. This lack of copper is a common feature of the tin-zinc-lead deposits of western Tasmania. The maximum development of copper in the Zeehan field is, however, found in the western part of the field (Silver Stream Mine) and this is in accordance with the zonal sequnces reported from other mineral fields.

Well-known examples of zoned copper-zinc-lead ores are the deposits of Butte (Sales, 1913; Hart, 1935; Sales and Meyer, 1948, 1949) Bingham (Peacock, 1958) and Central Peru (Petersen, 1965).

The Butte (Montana) deposits consist of three zones. The central zone consists largely of chalcocite, bornite and enargite, with some covellite and tetrahedrite. The intermediate zone consists of the same minerals as the inner zone and also chalcopyrite and tennantite, with sphalerite and galena occurring near the outer margin of this zone. The main constituents of the peripheral zone are sphalerite, galena and rhodocros_ite.

The Bingham (Utah) ores show a concentric arrangement with respect to the parent intrusive igneous body. The copper ores surround the porphyritic body, with lead-zinc and then silver-lead ores occupying outer zones.

Petersen (op. cit.) has reported that many of the complex copper-lead-zinc-silver deposits of Central Peru (e.g. Cerro de Pasco) show a zonal arrangement in which the copper ores predominate in the central zones, zinc in the intermediate zones and lead in the outer zones. The arsenic:antimony ratios are higher in the central zones and there is some evidence for a gradation from sulphur-rich to sulphur-deficient associations from central to outer zones.

The classic zoned deposits of Cornwall, England (Dewey, 1925), exhibit a greater variety of mineral zones than is observed at Zeehan, but the sequences are again comparable.

Reference has been made in a previous section to the deposits of the Central City district, Colorado, (Sims and Barton, 1961, 1962); these deposits show some similarities to the Zeehan deposits. The central zone consists essentially of pyrite and quartz, with some chalcopyrite, tennantite and gold near the outer margin of this zone. The major constituents of the intermediate zone are pyrite, quartz, sphalerite, galena and substantial amounts of gold and silver. The outer zone consists of sphalerite, galena and silver with a little chalcopyrite, tennantite and pyrite. As described previously, the composition of the sphalerite shows a decrease in iron content from the central to outer zone.

The literature on ore deposits contains many descriptions of zoned deposits and a comparison of these reveals a remarkable consistency in the observed zonal sequence of the minerals. The few deposits mentioned above serve to illustrate that, though the Zeehan ores differ from these deposits in terms of bulk composition, the respective zonal patterns are nevertheless comparable.

COMPARISON WITH OTHER ORE DEPOSITS OF WESTERN TASMANIA.

The mineral province of western Tasmania includes ores of tin, copper, zinc, lead, silver and tungsten. Hall and Solomon (1962) and Solomon (1965) have classified the various mineral deposits of Tasmania according to their spatial relationships to igneous rocks, and examples from western and north-western Tasmania and King Island are listed below.

Intra - magmatic deposits: cassiterite in granite (Heemskirk); chalcopyrite and pentlandite in serpentine (Cuni); magnetite in amphibolite (Savage River).

Contact metasomatic deposits: scheelite (King Island)

Deposits adjacent to granitic intrusions: Cassiterite with wolframite in discordant veins (Moina); cassiterite with pyrrhotite and pyrite in concordant replacement lenses (Mount Bischoff, Renison Bell); silver-rich lead and zinc ores in fissures (Magnet, Zeehan).

Deposits not obviously related to intrusions but associated with volcanic rocks: bornite, chalcopyrite and pyrite in volcanics (Mount Lyell); sphalerite galena and chalcopyrite in volcanics (Rosebery, Hercules).

The host rocks in this province range in age from Upper Proterozoic to Lower Devonian, but the most important are dolomites, shales and quartzites of Upper Proterozoic to

Lower Cambrian age, and the Cambrian Mount Read Volcanics. The deposits at Mount Bischoff, Magnet, Renison Bell and King Island, and many of the Zeehan deposits occur with the former group, and the Mount Lyell, Rosebery and Hercules deposits occur within the latter.

Several of the deposits located near granitic intrusions (in particular the King Island, Mount Bischoff and Renison Bell deposits) are also closely associated with carbonate sediments. This relationship suggests that carbonate instability may have been an important factor in localizing ore deposition in western Tasmania. If this is so, then it may explain the observed relationship between ore and spilite at Zeehan (see p. 287), since dolomite is also associated with the spilite (see p. 16) and could have provided a suitable horizon for replacement.

The relationship between the Zeehan field and nearby Dundas field (located six miles to the east of Zeehan) has yet to be fully investigated, but the two fields are apparently very closely related. The Dundas ores are similar to the Zeehan ores, and consist largely of galena and sphalerite with minor pyrite in a gangue of siderite. Many of the ore-bodies are fissure lodes within Upper Precambrian and Cambrian quartzite, slates and sandstones, and others are replacement lodes in dolomitized serpentinite. The tin ores of the Razorback and Grand Prix mines are mineralogically similar to the Renison Bell ores (cassiterite in pyrrhotite and pyrite).

Further work is required to provide a satisfactory explanation of the relationship between the Zeehan and Dundas fields, and it is possible that the two fields represent part of the same mineral field. However, the author considers it more likely that the Zeehan and Dundas area represent two separate but closely related fields, with the Dundas ores having been derived from an underlying cupola-type development of granitic material associated with the same intrusion as the Heemskirk Granite. This suggestion is illustrated diagrammatically in Figure 11.

CONCLUSIONS

A detailed mineralogical study has confirmed the observations of Waller (1904) and Twelvetrees and Ward(1910) that there is a considerable variation in the mineralogy of the ores from the Zeehan field. The compositions of the ore-bodies show a zonal arrangement with respect to the south-east margin of the Heemskirk Granite.

The zonal pattern indicated by the detailed mineralogy is, in many respects, similar to that proposed by Twelvetrees and Ward (op. cit.). The magnetite deposits located in altered ultrabasic rocks near the margin of the granite were not derived from the granite magma, but it is suggested that contact metamorphism caused the concentration of the magnetite.

It is also suggested that the more obvious horizontal component of the zoning was complicated by a vertical component, possibly due to a cupola-type development of granite underlying the Oonah - Queen Hill part of the field. A further cupola-type development may have accounted for mineralization in the Dundas area to the east of Zeehan.

There is no suitable geological thermometer applicable to the sulphide assemblages found in the Zeehan ores, and information on the temperatures of formation of the ores is rather sketchy. Arsenopyrite-pyrite assemblages indicate a maximum temperature of approximately 500°C for several of the ore-bodies, and pyrite-sphalerite assemblages suggest (but do not prove) a temperature gradient outward from the granite, possibly accompanied by a decrease in activity of sulphur.

Sulphur isotope analyses support the theory that the ores were derived from the granite magma, but also suggest that some of the sulphur was derived from crustal material assimilated during emplacement of the granite. This interpretation is supported by the work of Brooks and Compston (in press) and Heier and Brooks (in press), and by the sulphur : selenium ratios published by Edwards and Carlos (1954).

There is no single criterion which may be used to conclusively prove the origin of the Zeehan ores but mineralogical and geochemical evidence combined with the field work of previous investigators, strongly suggests that the Zeehan ores are of epigenetic origin and were deposited from solutions which emanated from the Devonian Heemskirk Granite.

It should be added that this investigation has revealed several further aspects which are worthy of additional study and which, if investigated, could add considerably to our knowledge of the Zeehan ores. These are as follows:

(1) More detailed work is needed on the sulphur isotope ratios and sulphur : selenium ratios of the ores from the Zeehan field and of samples from the Heemskirk Granite.

(2) A more detailed study is required of the variations in composition of sphalerite from the Zeehan field. This is at present being investigated by

Mr. K. L. Williams of the Australian National University.

(3) Siderite, being one of the most abundant minerals in this field, may warrant close geochemical investigation to see if significant variations in composition are present. A major difficulty in such a project would be in obtaining fresh samples.

(4) Since no suitable sulphide geological thermometer is available for studying the Zeehan ores, it may be desirable to investigate any fractionation of oxygen isotopes between coexisting quartz and siderite. Engel et al. (1958) and Clayton and Epstein (1961) have reported promising results in the use of oxygen isotopes in high-temperature geological thermometry, but, as far as the author is aware, quartz-siderite pairs have not yet been investigated. If it is found that there is a significant fractionation of the oxygen isotopes between these minerals, and if such fractionation is temperature dependent, then this system could provide a basis for study of the temperatures of formation of the Zeehan ores.

(5) The nickel minerals from the Central Balstrup Mine present an interesting mineralogical study. Electron-probe micro-analytical techniques are suggested as the most satisfactory method for further study of the mineralogy of this ore.

(6) As more reliable information is accumulated on the textural relationships of ore minerals it should be possible to make a more satisfactory interpretation of the paragenetic sequence of the ore minerals and its relationship to zoning. Present indications are that it will be many years before the textures of ore minerals can be clearly interpreted.

(7) The relationships between the Zeehan and Dundas mineral fields have yet to be investigated in detail by field or laboratory work.

(8) The magnetite bodies of the Comstock area require further field and laboratory investigation. Detailed petrological work is needed on the altered basic rocks which contain the magnetite.

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APPENDIX

Listed below are the polished and thin sections prepared for the study described in this thesis. All section numbers refer to the Tasmanian Museum catalogue of polished and thin sections. Material collected for this study has been accessioned into the mineral collection of the Tasmanian Museum, Hobart.

Polished Sections.

Polished section number (Tasmanian Museum catalogue)	Locality of specimen	Accession number of hand specimen.	Institution where specimen is housed.
P. 11	Oonah Mine	X.4911	Tasmanian Museum
12	" "	X.4911	"
13	" "	X.199	"
14	" "	X.199	"
15	" "	X.342	"
16	" "	X.2588	"
17	" "	X.2588	"
18	" "	X.2588	"
19	" "	X.2588	"
20	Oceana Mine	X.5198	"
21	" "	X.5199	"
22	" "	X.5199	"
23	" "	X.5200	"
24	" "	X.5200	"
25	Swansea Mine	X.2587	"
26	Zeehan Bell Mine	X.5203	"
27	" " "	X.5203	"
28	" " "	X.5204	"
29	" " "	X.5204	"
30	" " "	X.5205	"
31	" " "	X.5205	"

P.32	Zeehan Bell Mine	X.5205	Tasmanian Museum
33	" " "	X.5205	"
34	" " "	X.5206	"
35	" " "	X.5206	"
36	Silver King Mine	X.5210	"
37	" " "	X.5210	"
38	" " "	X.5210	"
39	" " "	X.5210	"
40	" " "	X.5210	"
41	Austral Valley	X.5215	"
42	" "	X.5216	"
43	" "	X.5216	"
44	" "	X.5216	"
45	" "	X.5217	"
46	Centmal Balstrup Mine	X.314	"
47	" " "	X.314	"
48	Manganese Hill	X.3279	"
49	Spray Mine	X.819	"
50	" "	X.492	"
51	" "	X.492	"
52	" "	X.235	"
53	Junction Mine	X.1877	"
56	" "	X.4894	"
65	No.4 Argent Mine	X.5218	"
66	" " "	X.5219	"
67	" " "	X.5219	"
68	" " "	X.5219	"
69	" " "	X.5219	"
70	" " "	X.5219	"
71	" " "	X.5219	"
72	" " "	X.5219	"
73	No.2 Argent Mine	X.5220	"
75	" " "	X.5220	"
76	" " "	X.5220	"
77	" " "	X.5221	"

P.	78	No.2 Argent Mine	X.5221	Tasmanian Museum
	79	" " "	X.5221	"
	80	" " "	X.5221	"
	81	" " "	X.5222	"
	82	" " "	X.5222	"
	83	" " "	X.5222	"
	84	Pyrite lode, north end of Queen Hill	X.5223	"
	85	Stormsdown Mine (Dunn's Tunnel)	X.5225	"
	86	" "	X.5225	"
	87	" "	X.5225	"
	88	Stormsdown Mine	X.5226	"
	89	" "	X.5226	"
	90	" "	X.5227	"
	91	" "	X.5227	"
	92	Zeehan Queen Mine	X.5228	"
	93	" " "	X.267	"
	94	" " "	X.4896	"
	95	" " "	X.4896	"
	96	Oonah Mine	X.4911	"
	97	" "	X.4911	"
	98	" "	X.5132	"
	99	Zeehan Queen Mine (Clarke's Tribute)	X.341	"
	100	Zeehan Queen Mine	X.5229	"
	101	" " "	X.5229	"
	102	" " "	X.5229	"
	103	Swansea Mine	X.5232	"
	104	" "	X.5232	"
	105	" "	X.2587	"
	106	Comstock Mine	X.279	"
	107	Zeehan-Montana Mine	X.270	"
	108	" " "	X.5133	"
	109	" " "	X.2083	"
	110	Montana Silver-Lead Mine	X.5233	"
	111	" " "	X.5234	"

P.	112	Montana Silver-Lead Mine	X.5235	Tasmanian Museum
	113	" " "	X.5235	"
	114	" " "	X.5236	"
	115	" " "	X.5236	"
	116	Swansea Mine	X.2587	"
	144	Silver King Mine	X.5211	"
	156	Oceana Mine	X.5202	"
	157	Comstock Mine	X.5238	"
	158	South Comstock Mine	X.5239	"
	159	" " "	X.5239	"
	160	" " "	X.5239	"
	161	" " "	X.5239	"
	162	" " "	X.5239	"
	163	Comstock Mine	X.5240	"
	164	" "	X.5240	"
	165	" "	X.5240	"
	166	" "	X.5241	"
	167	" "	X.5242	"
	168	" "	X.5242	"
	169	" "	X.5242	"
	170	" "	X.5242	"
	171	" "	X.5242	"
	172	" "	X.5242	"
	173	" "	X.5243	"
	174	" "	X.5244	"
	175	" "	X.5244	"
	176	" "	X.5244	"
	177	Tenth Legion Prospect	X.5245	"
	178	" " "	X.5245	"
	179	" " "	X.5245	"
	180	" " "	X.5245	"
	181	Zeehan Bell Mine	X.5208	"
	182	Swansea Mine	X.2587	"
	183	" "	X.5232	"

P.	184	Swansea Mine	X.2587	Tasmanian Museum
	185	" "	X.2587	"
	186	Tasmanian Crown Mine	X.5246	"
	187	Spray Mine	X.5247	"
	188	" "	X.5247	"
	189	" "	X.5247	"
	190	" "	X.5247	"
	191	" "	X.5248	"
	192	" "	X.5248	"
	193	" "	X.5249	"
	194	" "	X.5249	"
	195	" "	X.5249	"
	196	" "	X.5250	"
	197	" "	X.5250	"
	198	" "	X.5250	"
	199	" "	X.5250	"
	200	" "	X.5251	"
	201	" "	X.5251	"
	202	" "	X.5251	"
	203	" "	X.5251	"
	204	Montana Silver-Lead Mine	X.5232	"
	212	Oonah Mine	OS:33:819	Queen Victoria Museum (Launceston)
	213	" "	OS:33:819	"
	214	" "	OS:33:826	"
	215	" "	OS:33:826	"
	216	Silver Stream Mine	OS:33:838	"
	217	Central Balstrup Mine	1956:33:71	"
	218	" " "	1956:33:71	"
	220	Sunrise Mine	OS:33:105	"
	221	" "	OS:33:105	"
	222	Grubb's Mine	X.2559	Tasmanian Museum
	224	Sunrise Mine	X.2887	"
	227	South King workings (Fahey's tribute)	X.5176	"

P. 230	Zeehan Bell Mine	X.5209	Tasmanian Museum
231	Silver King Mine	X.5212	"
232	" " "	X.5214	"
236	Grubb's Mine	X.5252	"
237	Swansea Mine	X.5253	"
243	T. L. E. Mine	X.5254	"
245	Zeehan Queen Mine	X.5231	"
246	Nike Mine	X.5224	"
247	Zeehan Queen Mine	X.5230	"
248	" " "	X.2710	"
249	" " "	X.2934	"
250	" " "	X.2718	"
251	Montana Silver-Lead Mine	X.5237	"
254	Oceana Mine	X.5200	"
255	Oonah Mine	X.4911	"
256	Austral Valley	X.5216	"
257	Zeehan Bell Mine	X.5205	"
258	" " "	X.5205	"
259	Sunrise Mine	OS:33:105	Queen Victoria Museum (Launceston)
260	Silver King Mine	X.5215	Tasmanian Museum
261	Montana Silver-Lead Mine	X.5236	"
262	Tasmanian Crown Mine	X.5246	"
263	Junction Mine	X.4894	"
264	No. 4 Argent Mine	X.5219	"
265	Stormsdown Mine	X.5227	"
266	Silver Stream Mine	OS:33:838	Queen Victoria Museum (Launceston)
267	Comstock Mine	X.5238	Tasmanian Museum
268	Swansea Mine	X.5253	"
269	T. L. E. Mine	X.5254	"
270	Spray Mine	X.5249	"
271	Swansea Mine	X.2587	"
286	Zeehan-Montana Mine	X.5255	"

P. 287	Zeehan-Montana Mine	X.5255	Tasmanian Museum
288	" " "	X.5255	"
289	" " "	X.5255	"
290	" " "	X.5255	"
291	" " "	X.5255	"
292	Zeehan-Western Mine	11996	University of Tas. (Geology Department)
293	Zeehan-Western Mine	X.5256	Tasmanian Museum
294	" " "	X.5256	"
295	" " "	X.5256	"
296	Hanrahan's Adit	X.5196	"
297	Junction Mine	X.5197	"
298	" "	X.5197	"
299	" "	X.5197	"
300	Oonah Mine	X.5195	"
301	" "	X.5195	"
302	" "	X.5195	"
303	" "	X.5195	"
304	Stormsdown Mine	X.5257	"
305	" "	X.5258	"
306	" "	X.5259	"
307	Tasmanian Crown Mine	X.5260	"
308	Despatch Mine	X.5261	"
309	" "	X.5261	"
310	" "	X.5261	"
311	Nike Mine	X.5262	"
312	" "	X.5262	"
313	" "	X.5262	"
314	No.5 Argent Mine	X.5263	"
315	No.6 Argent Mine	X.5264	"
316	" " "	X.5264	"
317	" " "	X.5265	"
318	Sylvester Mine	X.5266	"
319	" "	X.5266	"
320	" "	X.5266	"

P. 321	Doric Mine	X.5267	Tasmanian Museum
322	" "	X.5267	"
323	" "	X.5267	"
324	" "	X.5267	"
325	Boss Mine	X.5269	"
326	" "	X.5269	"
327	" "	X.5269	"
328	" "	X.5269	"
329	Britannia Mine	X.5270	"
330	" "	X.5270	"
331	" "	X.5270	"
332	" "	X.5270	"
333	Doric Mine	X.5267	"
334	Grubb's Mine	X.5271	"
335	" "	X.5271	"
336	" "	X.5271	"
337	" "	X.5271	"
338	Nubeena Mine	X.5272	"
339	" "	X.5272	"
340	" "	X.5272	"
341	" "	X.5272	"
342	Tramway Formation (Colonel North Area)	X.5273	"
343	" "	X.5273	"
344	" "	X.5273	"
345	" "	X.5273	"
346	" "	X.5273	"
347	T. L. E. Mine	X.5274	"
348	" "	X.5274	"
349	" "	X.5274	"
350	" "	X.5274	"
351	" "	X.5275	"
352	Stonehenge Mine	X.5276	"
353	" "	X.5276	"
354	North Tasmanian Mine	X.5277	"
355	" " "	X.5277	"

P. 356	Tasmanian Mine	X.5278	Tasmanian Museum
357	" "	X.5278	"
358	" "	X.5278	"
361	Swansea Mine	X.5279	"
362	" "	X.5280	"
363	" "	X.5280	"
364	South Comstock Mine	X.5282	"
365	" " "	X.5282	"
366	" " "	X.5282	"
367	" " "	X.5282	"
368	Sweeney's Mine	X.5283	"
369	Swansea Mine	X.5281	"
371	Silver Stream Mine	X.5284	"
372	" " "	X.5284	"
373	Oonah Mine	X.4891	"
374	Grubb's Mine	X.4963	"
375	" "	X.4963	"
376	" "	X.4965	"
377	Zeehan-Western Mine	X.4969	"
378	" " "	X.4969	"
379	" " "	X.4968	"
380	" " "	X.4964	"
381	" " "	X.4967	"
382	Doric Mine	X.5268	"
384	Tasmanian Crown Mine	X.5285	"
385	" " "	X.5285	"
387	Sylvester Mine	X.2936	"
392	Zeehan Bell Mine	X.5203	"
393	T. L. E. Mine	X.5274	"
394	"Argent Mine"	X.2709	"
403	"Zeehan"	X.47	"

Thin Sections.

Thin section number (Tasmanian museum catalogue)	Locality of specimen	Accession number of hand specimen	Institution where specimen is housed
Ts. 1	Oceana Mine	X.5199	Tasmanian Museum
2	" "	X.5200	"
3	" "	X.5200	"
4	" "	X.5201	"
6	" "	X.5201	"
7	" "	X.5202	"
9	" "	X.5202	"
10	Oonah Mine	X.199	"
11	" "	X.2588	"
12	" "	X.2588	"
13	" "	X.2588	"
14	" "	X.2588	"
15	" "	X.2588	"
16	Zeehan Bell Mine	X.5203	"
17	" " "	X.5208	"
18	" " "	X.5204	"
19	" " "	X.5204	"
20	" " "	X.5207	"
21	" " "	X.5207	"
22	" " "	X.5205	"
23	" " "	X.5205	"
24	" " "	X.5205	"
25	" " "	X.5205	"
26	" " "	X.5206	"
27	" " "	X.5206	"
28	" " "	X.5206	"
29	" " "	X.5206	"
31	Silver King Mine	X.5210	"
32	" " "	X.5210	"

Ts.	33	Silver King Mine	X.5210	Tasmanian Museum
	34	" " "	X.5210	"
	35	" " "	X.5210	"
	36	" " "	X.5210	"
	37	" " "	X.5210	"
	38	" " "	X.5210	"
	39	" " "	X.5211	"
	40	Austral Valley	X.5215	"
	41	" "	X.5215	"
	42	" "	X.5215	"
	43	" "	X.5216	"
	44	" "	X.5216	"
	45	" "	X.5217	"
	46	" "	X.5217	"
	47	" "	X.5217	"
	48	" "	X.5217	"
	49	No.4 Argent Mine	X.5218	"
	50	" " "	X.5219	"
	51	" " "	X.5219	"
	52	" " "	X.5219	"
	53	No.2 Argent Mine	X.5220	"
	54	" " "	X.5220	"
	55	" " "	X.5222	"
	56	Pyrite lode, north end of Queen Hill	X.5223	"
	57	" " "	X.5223	"
	58	Stormsdown Mine (Dunn's Tunnel)	X.5225	"
	59	Stormsdown Mine	X.5226	"
	60	" "	X.5227	"
	61	" "	X.5227	"
	62	Zeehan Queen Mine	X.5228	"
	64	Swansea Mine	X.2587	"
	65	" "	X.2587	"
	66	" "	X.2587	"
	67	Montana Silver-Lead Mine	X.5235	"

Ts. 68	Montana Silver-Lead Mine	X.5235	Tasmanian Museum
71	" " "	X.5235	"
73	Comstock Mine	X.5242	"
74	" "	X.5242	"
75	" "	X.5244	"
77	Spray Mine	X.5247	"
79	" "	X.5250	"
110	Zeehan Bell Mine	X.5203	"
111	T. L. E. Mine	X.5274	"