Global comparisons of volcanic-associated massive sulphide districts

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Abstract: Although volcanic-associated massive sulphide (VMS) deposits have been studied extensively, the geodynamic processes that control their genesis, location and timing remain poorly understood. Comparisons among major VMS districts, based on the same criteria, have been commenced in order to ascertain which are the key geological events that result in high-value deposits. The initial phase of this global project elicited information in a common format and brought together research teams to assess the critical factors and identify questions requiring further research. Some general conclusions have emerged.

(1) All major VMS districts relate to major crustal extension resulting in graben subsidence, local or widespread deep marine conditions, and injection of mantle-derived mafic magma into the crust, commonly near convergent plate margins in a general back-arc setting.

(2) Most of the world-class VMS districts have significant volumes of felsic volcanic rocks and are attributed to extension associated with evolved island arcs, island arcs with continental basement, continental margins, or thickened oceanic crust.

(3) They occur in a part of the extensional province where peak extension was dramatic but short-lived (failed rifts). In almost all VMS districts, the time span for development of the major ore deposits is less than a few million years, regardless of the time span of the enclosing volcanic succession.

(4) All of the major VMS districts show a coincidence of felsic and mafic volcanic rocks in the stratigraphic intervals that host the major ore deposits. However, it is not possible to generalize that specific magma compositions or affinities are preferentially related to major VMS deposits world-wide.

(5) The main VMS ores are concentrated near the top of the major syn-rift felsic volcanic unit. They are commonly followed by a significant change in the pattern, composition and intensity of volcanism and sedimentation.

(6) Most major VMS deposits are associated with proximal (near-vent) rhyolitic facies associations. In each district, deposits are often preferentially associated with a late stage in the evolution of a particular style of rhyolite volcano.

(7) The chemistry of the footwall rocks appears to be the biggest control on the mineralogy of the ore deposits, although there may be some contribution from magmatic fluids.

(8) Exhalites mark the ore horizon in some districts, but there is uncertainty about how to distinguish exhalites related to VMS from other exhalites and altered, bedded, fine grained tuffaceous rocks.

(9) Most VMS districts have suffered fold-thrust belt type deformation, because they formed in short-lived extensional basins near plate margins, which become inverted and deformed during inevitable basin closure.

(10) The specific timing and volcanic setting of many VMS deposits, suggest that either the felsic magmatic–hydrothermal cycle creates and focuses an important part of the ore solution, or that specific types of volcanism control when and where a metal-bearing geothermal solution can be focused and expelled to the sea floor, or both.

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This and other questions remain to be addressed in the next phase of the project. This will include in-depth accounts of VMS deposits and their regional setting and will focus on an integrated multi-disciplinary approach to determine how mineralisation, volcanic evolution and extensional tectonic evolution are interrelated in a number of world-class VMS districts.

Volcanic-associated massive sulphide (VMS) deposits are one of the world's major sources of zinc, copper, lead, silver and gold (Fig. 1). These deposits form an important part of the metal-mining industry in Australia, Canada and Europe (Sweden, Spain, Portugal and Russia). Although studied extensively at the deposit and district scale, many questions remain about the fundamental geodynamic processes that control the genesis, deposit characteristics and the timing and location of major VMS deposits. The fundamental question of what controls the distribution and timing of world-class VMS ore deposits and districts cannot be answered by considering just one deposit, or even one mining district, but requires global comparisons among districts to determine which key geological events were common to districts with high-value deposits and/or numerous economic deposits. These comparisons need to be carried out using similar criteria and expertise in each district. The project reported here seeks to carry out these global comparisons. No such study has been attempted previously.

In most VMS districts there is one main stratigraphic position (or time line) on which the major VMS deposits are developed (Fig. 2). At the local scale, this time line commonly corresponds to a particular stage in the evolution of individual submarine volcanoes (e.g. Horikoshi 1969) and at the sub-regional scale it may represent a particular magmatic event in the evolution of the volcanic succession. At the mining district scale, this time line in turn represents a particular stage in the tectonic evolution of the whole region (e.g. Allen 1992). Defining the key magmatic/volcanic events and tectonic stage(s) that relate directly to major massive sulphide development, and exploring the connection between them from the local to regional scales, is critically important from both an ore genesis and mineral exploration perspective. By studying this problem in a series of global volcanic belts that host major VMS deposits, it should

Fig. 1. Location of major VMS districts, including (in black) districts involved in the Global VMS research project.

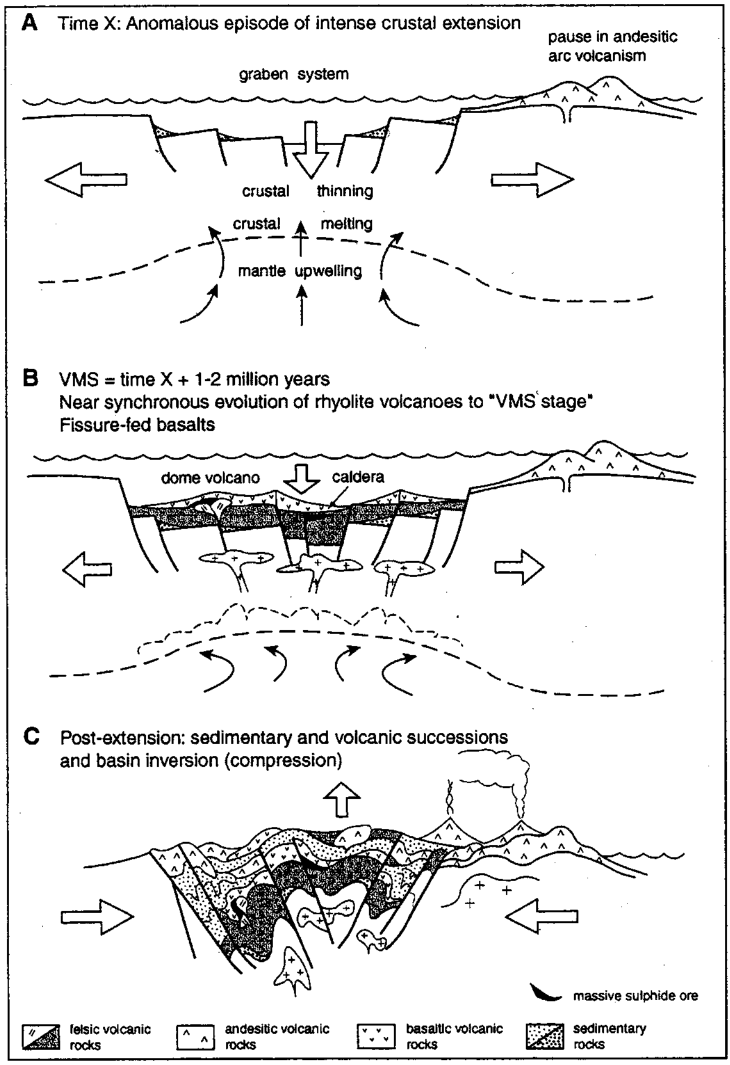

Fig. 2. Schematic tectonic-volcanic model encompassing the possible relationships between crustal-scale tectonism, volcanism and formation of VMS deposits. The model provides a theme that links the component studies of the Global VMS research project.

be possible to identify and compare these key events, and thus significantly improve our understanding of massive sulphide formation, and mineral exploration targeting. A further reason for choosing this approach is that the mining industry now operates with a global perspective and mining companies are interested in global scientific appraisals of important ore deposits. Consequently an aim of this project is to determine if it is possible to produce better genetic models for VMS deposits that can be applied globally.

This paper describes the start of the 'Global VMS research project' and provides preliminary results presented at the 'Volcanic Environments and Massive Sulphide Deposits' conference and associated workshop, Hobart, Tasmania in November 2000. In this contribution, emphasis is placed on comparing the tectonic and volcanic setting of VMS districts and deposits. Figure 2 provides the general context for the settings and evolution of many VMS districts, and serves as the theme that links our VMS studies.

A database of major VMS districts

For the reasons described above, the European Science Foundation GEODE (Geodynamics and Ore Deposit Evolution) programme and CODES (Centre for Ore Deposit Studies, University of Tasmania) set up a project in 1999, with a global perspective, to compare and contrast major VMS ore deposits and their settings. This brought together research teams conversant with the VMS provinces of Abitibi and the Bathurst Camp in

Canada, the Mount Read Volcanics in Tasmania, the Iberian Pyrite Belt (IPB) of Portugal and Spain, the Bergslagen and Skellefte districts in Sweden, and the southern Urals in Russia. Active plate tectonics, hydrothermal processes and mineralization in the Manus and Lau basins in the SW Pacific were included to provide modern analogues.

A database was developed by means of a questionnaire, drawn up by Professor Large (CODES). The questionnaire comprised a set of questions concerned with the tectonic and structural setting, timing and location of mineralization, volcanic architecture, styles of ore deposits, ore deposit characteristics, favourable horizons, exhalites, alteration facies, and mechanisms of ore genesis involving the metal and fluid sources, plumbing and fluid circulation, fluid–rock interactions and the thermo-mechanical driving forces. Each team responded with the relevant information, based on the current state of knowledge, to create a database with which to compare features in a consistent fashion. The database is accompanied by a bibliography of the key publications relating to each of the VMS districts. The data have been compiled on CD-ROM and are freely available from CODES. They provide systematic information on what is known about the VMS deposits and also indicate where there are gaps in knowledge. The teams met at a workshop held in Hobart, Tasmania in November 2000, to appraise the data. A summary of the results of the workshop is provided in this paper.

Brief descriptions of some major VMS districts

Eleven regions with major VMS deposits are briefly described below. They are arranged according to their stratigraphy and interpreted tectonic setting, from island arc terranes and rifted continental margin arcs (Green Tuff Belt, Skellefte, Urals), to rifted continental margins without thick andesitic arc successions (Lachlan Fold Belt, Bathurst, Mount Read Volcanics), to continental margin regions with anomalously intense felsic volcanism (Bergslagen) and relatively minor volcanism (Iberian Pyrite Belt), to an Archaean province (Abitibi) and two young back-arc basins that contain VMS mineralization (Lau and Manus Basins). The young age (Miocene) and extensive research of the Green Tuff belt have enabled the construction of a more detailed and reliable record of this belt's evolution than most, if not all, other VMS districts. Consequently, the Green Tuff belt is described in more detail than the other regions.

Green Tuff Belt, Japan

The Japan volcanic arc is built on 30 km thick, Palaeozoic–Oligocene continental crust and was part of a continental margin arc along the eastern margin of the Eurasian continent from at least the Cretaceous to the Early Miocene (about 70–24 Ma) (Taira *et a*l. 1989). Japan separated from the Eurasian continent during back-arc extension in the Late Oligocene–Middle Miocene (28–14 Ma) (Otofuji *et al.* 1985; Tamaki *et al.* 1992). The back-arc basin is mainly floored by extended continental crust. New oceanic crust formed by spreading is known in only a part of the basin. The Green Tuff belt (Fig. 3) represents the marine volcanic and sedimentary succession that formed along the eastern, arc-side of the back-arc basin in response to rifting (Ohguchi *et al.* 1989). The belt is 1500 km long and contains a complex, 1–5 km thick, Lower Miocene to Lower Pliocene (24–4 Ma) volcanic stratigraphy. The belt contains many massive sulphide (kuroko) districts. However, the most famous and important is the Hokuroku district in northern Honshu (Fig. 3), which contains eight main clusters of massive sulphide lenses and several other scattered smaller deposits (Ishihara *et al.* 1974; Ohmoto & Skinner 1983).

Along the far western side of Japan, including Oga Peninsula (Fig. 3), the type area of the Green Tuff, alkaline to calc-alkaline andesite and lesser basalt and rhyolite were erupted in a subaerial to littoral environment during the Late Oligocene to Early Miocene (35–24 Ma) (Ohguchi 1983; Ohguchi *et al.* 1989, 1995). This volcanism migrated eastwards towards the trench from 30–20 Ma (Ohguchi *et al.* 1989) and appears to have been a precursor to major back-arc rifting, which commenced at 28–21 Ma (Otofuji *et al.* 1985; Tamaki *et al.* 1992). Rifting peaked at 16–15 Ma, when there was a strong rotation of the Japanese arc (Otofuji *et al.*1985), a peak in the marine transgression, and rapid fault-controlled subsidence of up to 3 km in 1 million years, which formed deep marine grabens along the western side of Japan (within the Green Tuff belt) (Yamaji & Sato 1989; Sato & Amano 1991). Intense basalt-dominant bimodal (basalt–rhyolite) submarine volcanism closely followed this rapid subsidence along the present Japan Sea Coast of northern Honshu, and intense rhyolite-dominant bimodal submarine volcanism and the kuroko mineralization followed the subsidence in the present Backbone Ranges belt to the east. The basalts are tholeiitic to transitional in composition, whereas the rhyolites are calc-alkaline (Konda 1974; Dudás *et al.* 1983). The crustal stress regime at this time, determined from the orienta-

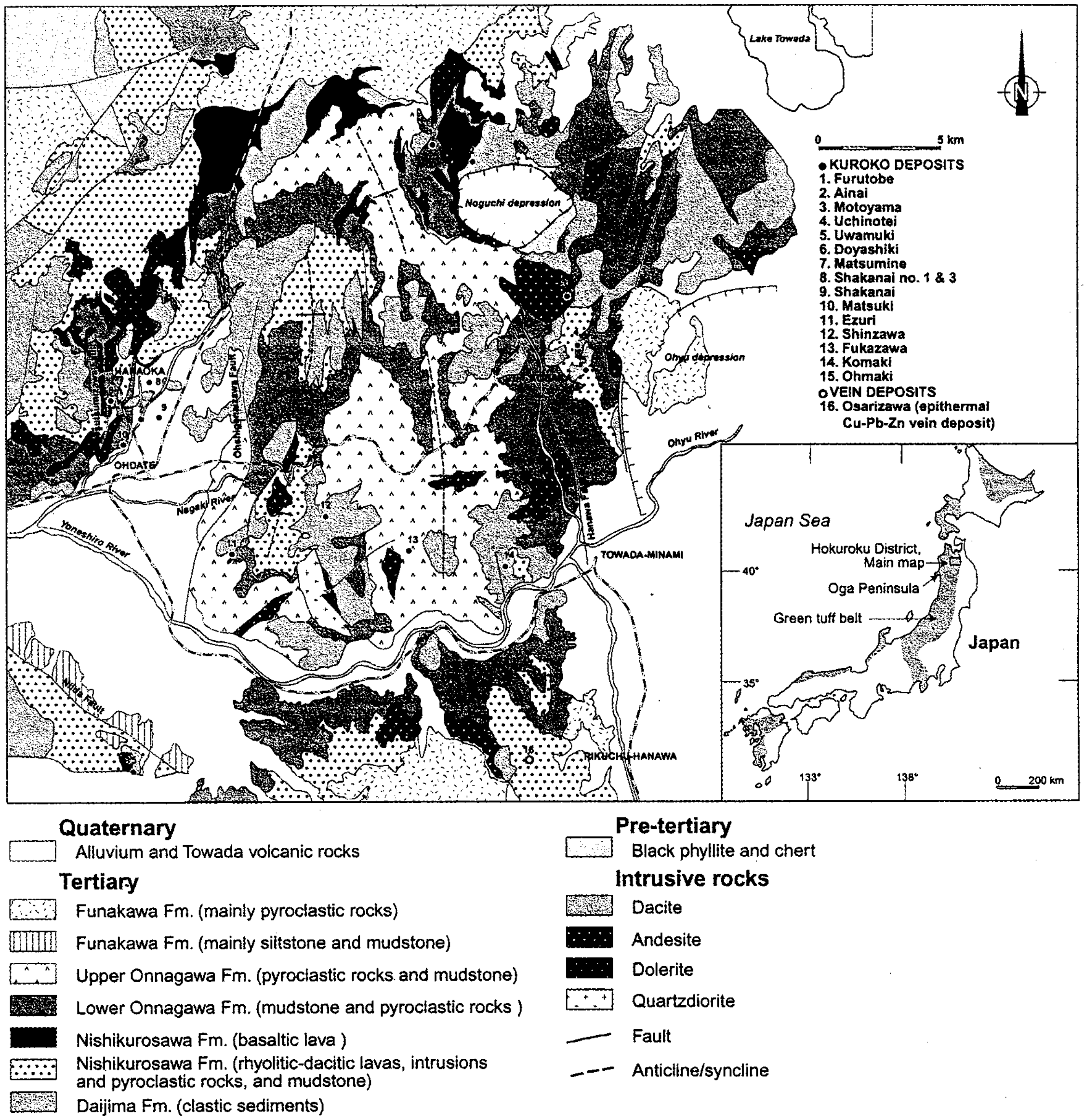

Fig. 3. Summary geological map of the Hokuroku VMS district. Modified from Tanimura *et al.* (1983).

tion of dykes, faults and veins, comprised east–west to SE–NW extension (Yamagishi & Watanabe 1986; Sato 1994).

The intense early Mid Miocene (16–15 Ma) subsidence was followed (Mid–Late Miocene, 14–10 Ma) by a transitional stress field and slow (thermal) subsidence (Sato & Amano 1991; Sato 1994). Bimodal volcanism continued from about 16–12 Ma, then changed to more typical arc-composition calc-alkaline andesite–dacite–rhyolite volcanism (Konda 1974; Okamura 1987). In the Japan Sea coast area, the slow subsidence continued into the Early Pliocene (14–3 Ma) and a thick, deep marine mudstone–turbidite succession with subordinate volcanic rocks accumulated. However to the east, the present Backbone Ranges, including the major Kuroko districts, began to uplift during the Late Miocene–Early Pliocene (10–3 Ma) and numerous felsic caldera volcanoes formed in terrestrial to shallow marine environments. This uplift and volcanism may have been caused by igneous underplating (Sato 1994). A compressional stress regime and reactivation of the Miocene normal faults as thrusts commenced in the Late Pliocene, and resulted in widespread terrestrial conditions and the onset of the present arc regime (Yamagishi & Watanabe 1986; Sato 1994).

The kuroko deposits occur in a narrow time-stratigraphic interval (Mid Miocene 15–12 Ma) within the deep marine, bimodal (rhyolite–basalt) volcanic successions. The Miocene strata are mainly gently dipping, but complex volcanic facies architecture and abundant normal faults make it difficult to correlate stratigraphy from one submarine volcano or fault block to the next. Where the volcanic rocks are interbedded with mudstones, fossil control (mainly foraminifera, nannofossils) enables resolution of 2–3 Ma time-stratigraphic intervals. In the Hokuroku district, the volcanic succession comprises a lower, 300–1000 m thick, massive rhyolite–basalt complex and an overlying 300–1000 m thick, more stratified succession dominated by alternating tuffaceous mudstone and thick subaqueous mass flow units of felsic pyroclastic debris. The lower volcanic complex comprises several overlapping volcanic centres dominated by felsic lava domes, intrusive domes and related autoclastic and pyroclastic rocks (Horikoshi 1969; Ishihara *et al.* 1974). The kuroko deposits are Zn–Pb–Cu–Ag–Au type VMS deposits that formed on and below the seafloor, mainly in the upper, proximal (near vent) part of these volcanoes (Horikoshi 1969).

The name 'Green Tuff' is derived from the various shades of green of the volcanics due to marine diagenetic and hydrothermal alteration, and the tuffaceous (pyroclastic) origin ascribed to many of the rocks. The regional diagenetic alteration is characterized by a vertical zonation of clays (especially montmorillonite and saponite) and zeolites (Iijima 1974), formed under high geothermal gradients of over 100 °C km^{-1} (Utada 1991). The kuroko deposits are enclosed by local hydrothermal alteration that overprints and interfingers with the diagenetic alteration, and is zoned from the ore deposit to the margin as follows: quartz–K-feldspar, kaolinite, sericite–chlorite, montmorillonite–illite, montmorillonite and analcite–calcite (Iijima 1974; Utada 1991).

Skellefte district, northern Sweden

The Skellefte district (Fig. 4) is a 120 × 30 km Early Proterozoic (1.90–1.88 Ga) magmatic region that contains over 80 massive sulphide deposits (Rickard 1986; Weihed *et al.* 1992). The district lies between a region of continental, mainly felsic, volcanic rocks of similar to slightly younger age to the north, and a large region of deep marine sedimentary and subordinate mafic volcanic rocks, intruded by numerous granitoids, to the south and east. The marine sedimentary succession south of the Skellefte district appears to span an age range from older than to younger than the Skellefte district volcanic rocks (Lundqvist *et al.* 1998).

The Skellefte district contains a >7 km thick stratigraphy of calc-alkaline basalt–andesite–dacite–rhyolite, tholeiitic basalt–andesite–dacite, high Mg (komatiitic) basalt and subordinate sedimentary rocks, and is intruded by syn- and post-volcanic granitoids (Fig. 4; Vivallo & Claesson 1987; Allen *et al.* 1996*b*). The rocks are generally strongly deformed, steeply dipping and are metamorphosed from greenschist to amphibolite facies. Primitive isotopic signatures suggest that magmas were mainly mantle-derived (Billström & Weihed 1996). The stratigraphy is very complex, laterally variable, diachronous, and marker horizons are rare. The only consistent regional stratigraphic pattern is a first order cycle comprising a lower >3 km thick marine volcanic complex (*c.* 1882–1890 Ma), overlain diachronously by a >4 km thick, mixed sedimentary and volcanic sequence. The lower volcanic complex consists of interfingering and overlapping rhyolite, dacite–andesite and basalt–andesite–dacite volcanoes (Allen *et al.* 1996*b*). However, about 50% of the volcanic rocks are rhyolites. Subaqueous lava, intrusion, autoclastic and pyroclastic facies are all common. Deep subaqueous (below wave base) depositional environments are dominant throughout the lower volcanic complex, which indicates that strong extension and subsidence preceded and/or accompanied the volcanism (Allen *et al.* 1996*b*). The overlying mixed sedimentary and volcanic sequence records uplift, erosion and renewed rifting, and includes medial–distal facies of the voluminous continental felsic magmatism (1877 Ma) that occurred directly north of the Skellefte district. The stratigraphic architecture, range of volcanic compositions and abundance of rhyolites suggest that the Skellefte district is a remnant of a strongly extensional intra-arc region that developed on continental or mature arc crust.

Most VMS deposits in the Skellefte district occur in near-vent facies associations at the top of local volcanic cycles (volcanoes), especially rhyolitic dome-tuff cone volcanoes (Allen *et al.* 1996*b*). Regionally, these VMS deposits occur on at least two stratigraphic levels, but the highest concentration occurs near the upper contact of the main volcanic complex. The VMS deposits span a wide range in composition, geometry and alteration patterns: the main compositional types are Au–As–Cu–Zn, pyritic Zn–Pb–Cu–Au–Ag and pyritic Zn–Cu–Au–Ag deposits. Several deposits are Au-rich. The deposits are associated with strong quartz–sericite, chlorite (or phlogopite–cordierite), andalusite–muscovite and carbonate alteration.

Urals

The Urals orogenic belt extends for 2500 km and is up to 200 km wide. The main VMS deposits are confined to the southern half of the belt (Fig. 5).

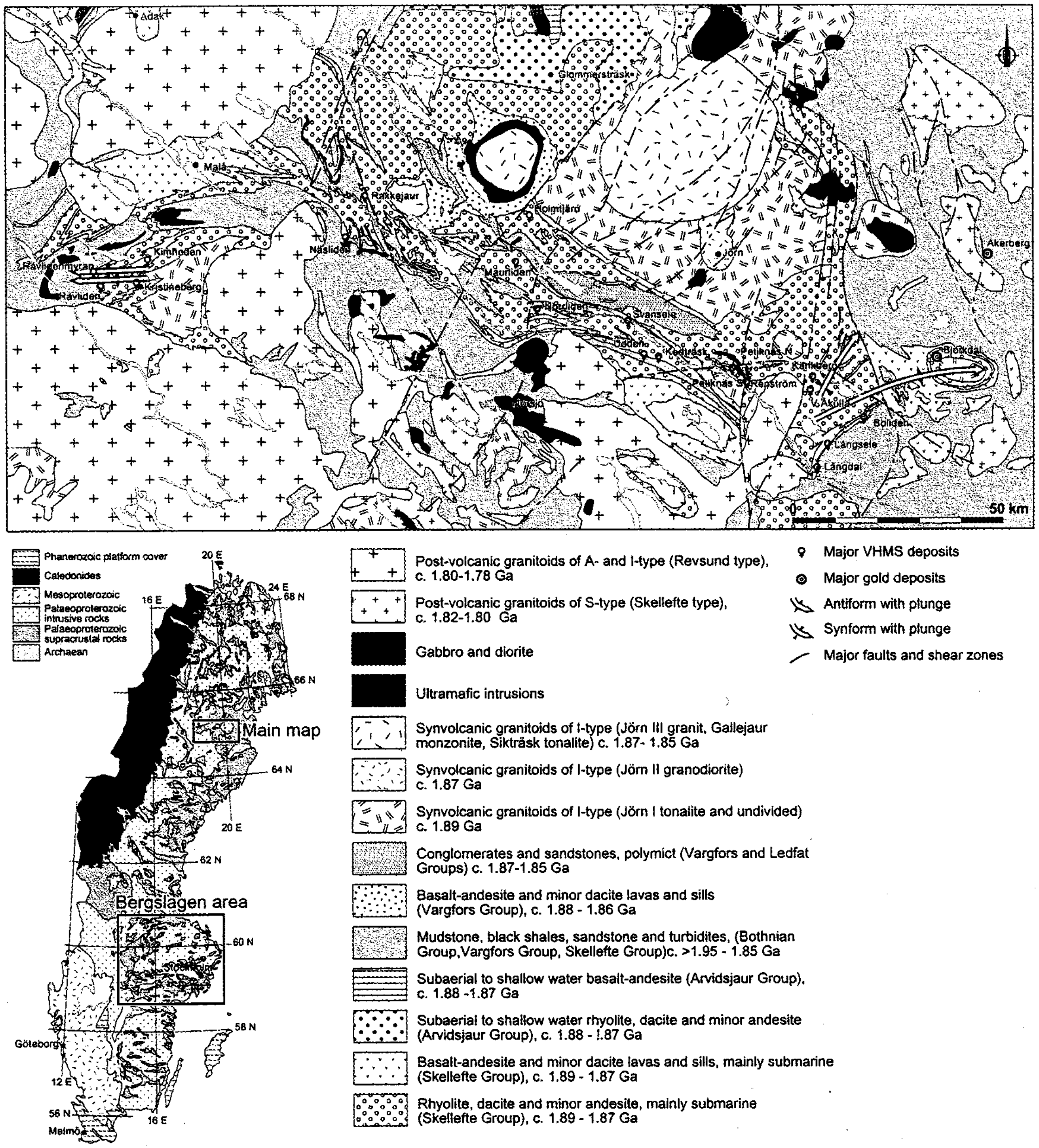

Fig. 4. Summary geological map of the Skellefte VMS district. Modified from Allen *et al.* (1996b).

They fall into two main age groups, Ordovician–Silurian and Devonian. The former group occurs west of the Main Urals Fault, which marks the suture representing the closure of the Palaeozoic Urals palaeo-ocean, and the latter group occurs to the east of the suture (Koroteev *et al.* 1997; Puchkov 1997). Altogether the various types of VMS deposits have a pre-mining tonnage of over 1000 Mt (Prokin & Buslaev 1999; Herrington 1999; Herrington *et al.* 2000).

The southern Urals can be further divided from west to east into the Sakmara Zone (SZ), the Main Uralian Fault Zone (MUFZ) and the Mednogorsk Island Arc System (MIAS), all sub-parallel to the Main Uralian Fault (Fig. 5; Puchkov 1997; Koroteev *et al.* 1997; Herrington 1999; Herrington *et al.* 2000). The Urals palaeo-ocean was initiated at *c.* 460 Ma. The first known island arc terrane comprises Silurian volcanics in the SZ and these rocks host the oldest VMS deposits. The initiation of the Magnitogorsk island arc, located east of the MUFZ, started around 390 Ma with Caledonian collision between Baltica and Siberia. The arc sequence collided with the East European Continent diachronously, at around 360 Ma in the southern Urals, and in the Carboniferous in the

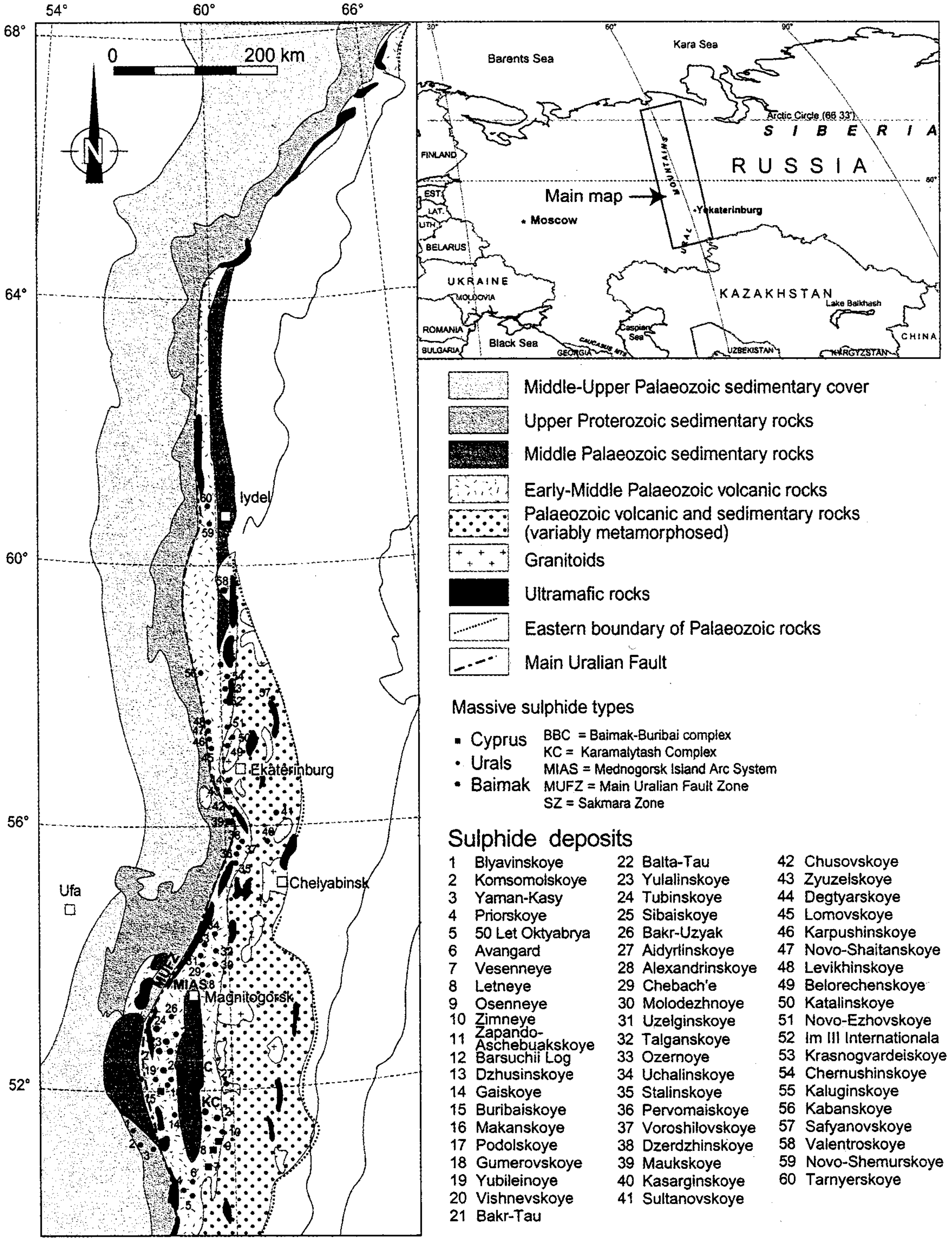

Fig. 5. Summary geological map of the southern Urals VMS district. Modified from Prokin *et al.* (1998).

central Urals. Subsequently, there was an easterly shift and an apparent switch in polarity of subduction prior to final continent–continent collision. At the western margin of the MUFZ, 400 Ma old boninites record the onset of eastward intraoceanic subduction, followed by an eastward temporal and spatial progression of several arc-volcanic complexes. Approach of the East European continental margin to the subduction zone, resulted in arc–continent collision (Puchkov 1997; Brown & Spadea 1999).

Arc-related VMS deposits are confined to the Baimak–Buribai Complex (BBC) and the Karamalytash Complex (KC) (Koroteev, *et al.* 1997; Prokin & Buslaev 1999; Herrington 1999; Herrington *et al.* 2000). The VMS deposits span a range in types and compositions but are dominated by Cu–Zn, Cu and Pyrite types. The allochthonous oceanic fragments of the Sakmara Zone contain the Cu–Zn VMS deposits of the Mednogorsk district, associated with areas of andesite-felsic rocks. The MUFZ contains several small uneconomic serpentinite- and basalt-hosted massive sulphides of debatable origins. The VMS deposits of the MIAS are associated with intermediate-felsic successions in the western MIAS and with felsic–mafic successions in the eastern MIAS.

Coherent lava flows are interpreted to be much more abundant than volcaniclastic rocks in the vicinity of the VMS deposits and many deposits are associated with rhyolitic–dacitic domes. The roofs of plagiogranite intrusions have been drilled below some of the VMS deposits. The deposits have extensive footwall alteration and most show clear evidence of having formed on the seafloor. The largest deposits are thought to be concentrated on two or three stratigraphic levels within each terrane (Herrington 1999; Herrington *et al.* 2000).

Lachlan Fold Belt, SE Australia

The Lachlan Fold Belt contains a >10 km thick Cambrian to Carboniferous stratigraphy that records a complex history of basin development, waves of diachronous deformation, magmatism, accretion and continental growth at the eastern margin of Gondwana (Cas 1983; Gray *et al.* 1997). Although there is no preserved distinct andesitic volcanic arc, the pattern of sedimentation, magmatism and deformation is attributed to plate convergence and subduction.

During the mid-late Silurian, a series of graben basins and widespread shallow and deep marine environments developed over an area of at least 600 by 400 km in response to transtension along the continental margin (Powell 1983). An enormous volume of S- and I-type granitoid magma was also intruded to high crustal levels in this area from Late Silurian–Early Devonian. The basins and granitoids are interpreted to have formed in a segment of continental crust between converging oceanic crust to the east and a marginal basin to the west (Gray *et al.* 1997). The mid-late Silurian basins thus have an essentially ensialic intra-arc rift setting (Cas & Jones 1979). The basins have broadly similar stratigraphies, suggesting a common evolutionary cycle (Allen 1992): (1) crustal-derived felsic magmatism formed volcanic piles up to 3 km thick in terrestrial to shallow marine environments with fringing carbonate reefs and platforms, then (2) graben subsidence to deep marine conditions during the late stage of felsic volcanism, (3) accumulation of deep marine sediments and local eruption of rhyolite and mantle-derived basalt ± andesite–dacite within the grabens and finally (4) closure and uplift (structural inversion) of the basins between the end of the Silurian and Mid-Devonian. The Silurian basin successions were strongly deformed and metamorphosed to greenschist facies at this time.

VMS deposits formed in the grabens directly after initial deep subsidence. They formed in the vent areas of rhyolite dome volcanoes near the top of the felsic successions, at the time and place where mantle derived basalt ± andesite–dacite first erupted (Allen 1992; Stolz *et al.* 1997). The deep marine volcanic rocks are mainly lavas and their autoclastic facies, shallow sills, and mass flow units of pyroclastic debris that were shed into the basins from the basin margins. The VMS deposits are associated with strong quartz–sericite and chlorite alteration.

Bathurst

The Bathurst mining camp in eastern Canada comprises a 100 × 75 km area of complexly deformed Ordovician (480–457 Ma) volcanic and sedimentary units intruded by syn-volcanic plutons (Fig. 6). The region is interpreted as an ensialic back-arc basin that was strongly deformed and metamorphosed to upper greenschist facies during closure of the basin in the Late Ordovician to Late Silurian (van Staal 1987).

The district hosts about 35 VMS deposits of Pb–Zn–Cu–Ag type with a total tonnage of over 250 Mt (McCutcheon 1992). The deposits are associated with a bimodal, rhyolite–rhyodacite dominated, marine volcano-sedimentary sequence. The felsic rocks are attributed to partial melting of the continental basement, whereas the mafic rocks are tholeiitic to alkaline basalts (Lentz 1999). In the Brunswick belt, the most productive part of the district, the VMS deposits formed directly after a major episode of felsic pyroclastic volcanism (Nepisiguit Falls Formation of the Tetagouche Group) and before the deposition of overlying rhyolitic lavas, hyaloclastites, tuffs and tuffaceous sedimentary rocks. The large volume of juvenile pyroclastic rocks in the footwall to the ore deposits suggests that the ores may have formed in calderas following climactic eruption and cal-

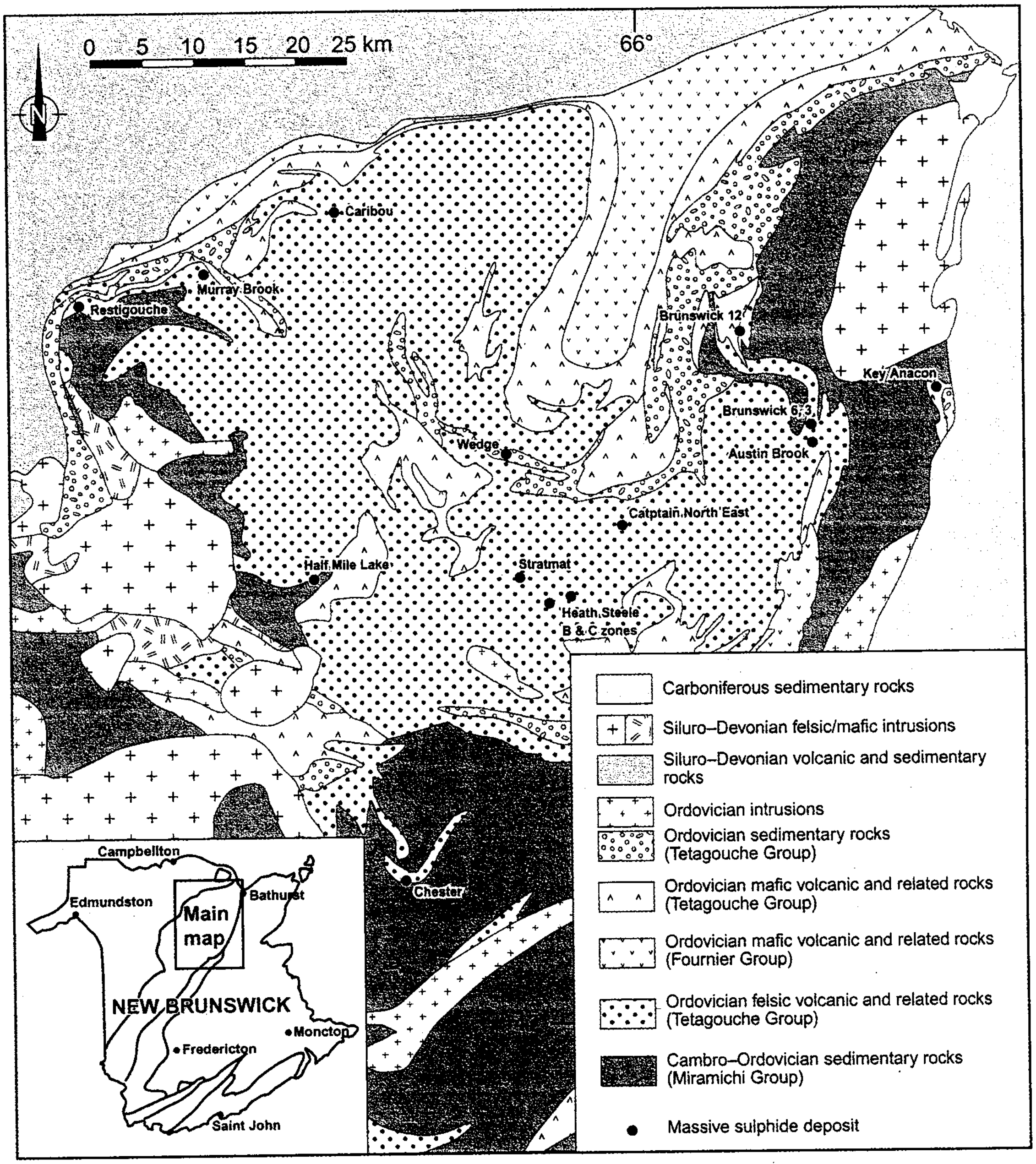

Fig. 6. Summary geological map of the Bathurst VMS district. Modified from Lentz (1999).

dera subsidence. However, details of the volcanic architecture are not known.

The VMS deposits are mainly of stratiform-type, are hosted by fine-grained volcaniclastic and sedimentary rocks, and are in part associated with iron formation exhalites that generally extend <1 km along strike, but locally up to 5 km (Saif 1983; Peter & Goodfellow 1996). The deposits are interpreted to have formed in deep to very deep water. Some other deposits are stratabound and occur in first or second-cycle felsic fragmental rocks.

Mount Read Volcanics, Tasmania

This region comprises a 200 × 20 km area of Cambrian, moderately to strongly deformed, mainly felsic volcanic rocks and volcano-sedimentary successions, lying on and between a series of Precambrian basement blocks near a margin of the Gondwanan continent (Fig. 7; Corbett 1992). The district contains a series of rich VMS deposits that span a wide range in deposit styles (Green *et al.* 1981; Large *et al.* 1988; Gemmell & Large 1992; Large 1992; Halley & Roberts 1997; Solomon &

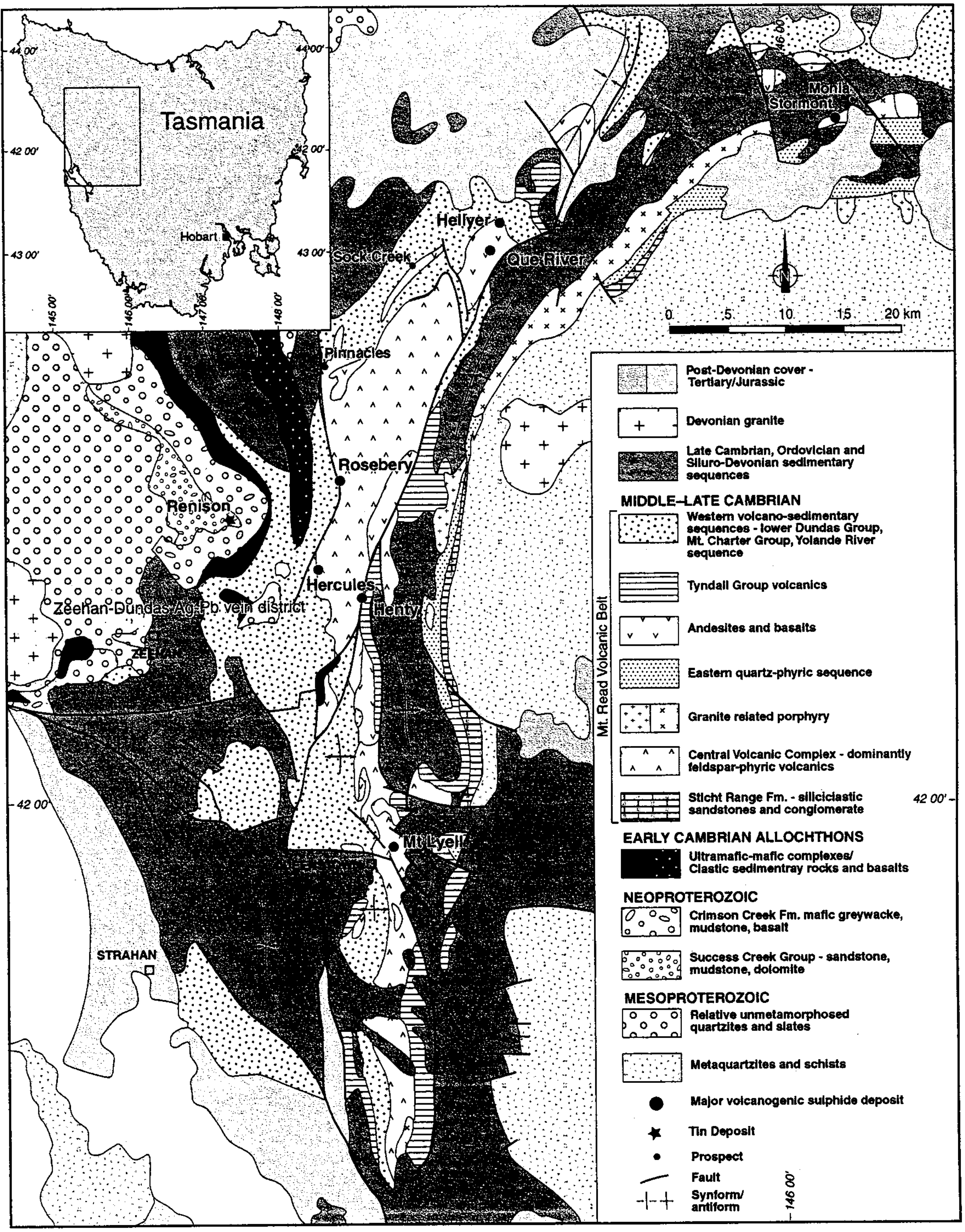

Fig. 7. Summary geological map of the Mount Read Volcanic VMS district. Modified from Corbett (1992).

Khin Zaw 1997; Corbett 2001). Metamorphic grade is mainly lower greenschist facies.

In the central, best-known part of the district, the lowest exposed stratigraphic unit is a >1 km thick, marine tholeiitic basalt–andesite volcanic complex. This is overlain by the 3 km thick Central Volcanic Complex (CVC), which is a mass of interfingering calc-alkaline dacite–rhyolite lavas, pyroclastic facies, shallow intrusions and local medium- to high-K calc-alkaline andesite, all emplaced in a shallow to deep marine environment (Corbett 1992). The CVC is onlapped to the west and north by a >3 km thick, deep marine, mixed volcanic–sedimentary succession (Mt Charter Group) with calc-alkaline andesites, dacites and rhyolites, and medium-K to shoshonitic basalt–andesite. The CVC is overlain to the east by a 1 km thick, shallow marine to subaerial, rhyolitic succession with lesser basalt (Tyndall Group). Cambrian granites, contemporaneous with the volcanic rocks, occur in a belt along the eastern side of the Mount Read Volcanics (Large *et al.* 1996). Regional stratigraphic relationships are complex, laterally variable, and correlations are difficult to demonstrate (McPhie & Allen 1992; Corbett 1992). The Mount Read Volcanics are attributed to a period of extension on the Gondwanan continental margin, but the details are still debated. Crawford *et al.* (1992) argued that extension was related to crustal collapse after an intra-oceanic arc and fore-arc complex collided with, and was overthrust onto, the Gondwanan passive margin.

VMS deposits are interpreted to lie in two main stratigraphic settings: (1) at the top of the CVC in vent areas of major rhyolite–dacite volcanoes (Rosebery, Hercules, Mt Lyell deposits) and (2) in proximal (near-vent) facies associations at the top of andesite–dacite volcanoes in the mixed volcanic–sedimentary succession (Hellyer, Que River deposits). Strong quartz–sericite, chlorite, silicification and carbonate alteration are the main alteration types associated with the VMS deposits.

Bergslagen, central Sweden

Bergslagen (Fig. 4) is the intensely mineralized part of a 280 × 300 km, Early Proterozoic (1.90–1.87 Ga) felsic magmatic region of mainly medium to high metamorphic grade. The volcanic succession is 1.5 km thick and overlies turbiditic metasedimentary rocks in the east, and is over 7 km thick with no exposed base in the west (Lundström 1987; Allen *et al.* 1996*a*). Basement is interpreted to be Precambrian continental crust.

The volcanic succession is overwhelmingly (90%) calc-alkaline rhyolite with minor calc-alkaline dacite and andesite, and chemically unrelated, probably tholeiitic basalts. Strong K-feldspar and albite alteration occur on a regional scale, whereas Mg-alteration (talc, chlorite, phlogopite, cordierite, skarn) is more local and spatially closely associated with mineralization (Lagerblad & Gorbatschev 1985). The stratigraphy commonly follows the pattern. (1) Lower 1–5 km thick, poorly stratified felsic complex, dominated by the proximal–medial facies of interfingering and overlapping large caldera volcanoes, and minor interbedded limestone. (2) Middle 0.5–2.5 km thick, well stratified interval dominated by medial–distal juvenile volcaniclastic facies and limestone sheets. (3) Upper >3 km thick post-volcanic argillite–turbidite sequence (Baker *et al.* 1988; Allen *et al.* 1996*a*). Depositional environments fluctuated mainly between shallow and moderately deep subaqueous throughout accumulation of the lower and middle stratigraphic intervals, then became consistently deep subaqueous in the upper interval.

The supracrustal succession has been intruded by an enormous volume of syn- and post-volcanic granitoids and has been strongly deformed, such that it now occurs as scattered, tightly folded outliers, enveloped by granitoids. The stratigraphy reflects an evolution from intense magmatism, thermal doming and crustal extension, followed by waning extension, waning volcanism and thermal subsidence, then reversal from extension to compressional deformation and metamorphism. The region is interpreted as an intra-continental, or continental margin back-arc, extensional region (Baker *et al.* 1988; Allen *et al.* 1996*a*).

Bergslagen has a diverse range of ore deposits, including banded iron formation, magnetite–skarn, manganiferous skarn- and limestone-hosted iron ore, apatite–magnetite iron ore, stratiform and stratabound Zn–Pb–Ag– (Cu–Au) sulphide ores, and W skarn (Hedström *et al.*1989; Sundblad 1994; Allen *et al.* 1996*a*). The massive and semi-massive base-metal sulphide ores occur in interbedded limestone and volcaniclastic rocks, especially near the top of the volcanic succession. These ores occur close to proximal felsic volcanic facies and anomalous concentrations of basalt intrusions and lavas.

Iberian Pyrite Belt

The Iberian Pyrite Belt (IPB) is a 250 × 60 km belt of Upper Devonian–Lower Carboniferous sedimentary and volcanic rocks (Fig. 8), which hosts about 90 massive sulphide deposits, including eight extremely large deposits with more than 100 Mt of massive sulphide (Schermerhorn 1975; Carvalho *et al.* 1997; Leistel *et al.* 1998). It is part of the South Portuguese Zone (SPZ), the southernmost fold and thrust terrane of the Variscan orogen in Europe (Silva *et al.* 1990; Quesada 1998).

Most authors attribute the IPB to crustal extension and related magmatism, that were triggered by oblique collision of the continental SPZ with the active margin of the Iberian block to the north (Quesada 1991, 1998; Leistel *et al.* 1998; Tornos *et al.* 2002). Pull-apart graben basins with bimodal volcanic successions and VMS deposits formed in

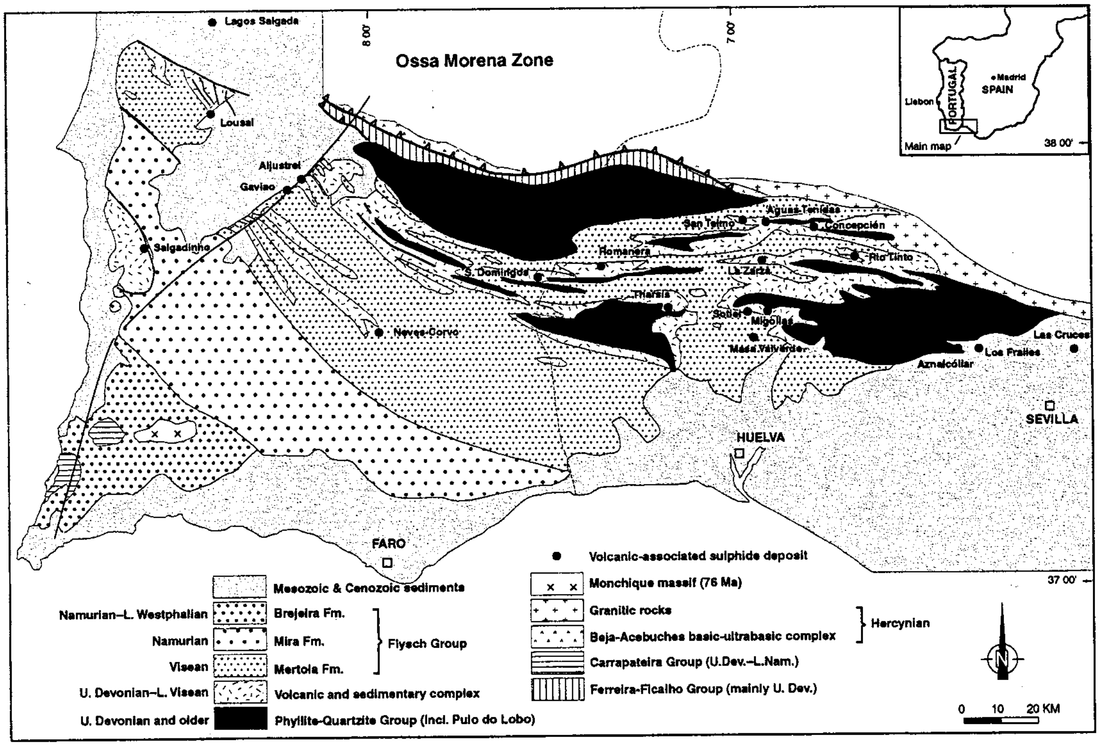

Fig. 8. Summary geological map of the Iberian Pyrite Belt VMS. Modified from Carvalho *et al.* (1997).

the IPB during this oblique collision. Continued collision ultimately resulted in obduction of the Iberian margin onto the SPZ, inversion of the extensional basins, and southward propagation of the SPZ fold and thrust belt.

The IPB has a relatively simple regional stratigraphy that can be divided into three distinct intervals. From base to top these are: (1) >1000 m of Upper Devonian terrigenous siliciclastic rocks and minor limestone, deposited on a shallow marine continental platform. (2) A 20–1000 m thick, mixed volcanic–sedimentary interval, comprising grey-black deep-water mudstones with intercalated rhyolitic–dacitic, basaltic, and lesser andesitic rocks. Basalts are tholeiitic whereas the other volcanic rocks are mainly calc-alkaline and interpreted to be partial melts of continental crust (Thieblemont *et al.* 1998). Shallow sills and associated autoclastic facies appear to be the most abundant volcanic facies, followed in abundance by lava domes/lobes and associated autoclastic facies and pyroclastic facies (Boulter 1993; Soriano & Martí 1999; Tornos *et al.* 2002). The facies pattern indicates a regionally extensive sill–lava lobe complex without distinct, large constructional volcanoes. VMS deposits and Jasper and Mn–Fe formations occur in the upper part of the volcano-sedimentary interval. In the southern part of the IPB, a prominent 5–40 m layer of red, oxidized, shallow-water volcaniclastic sediments occurs near the top of the volcano-sedimentary interval, and grades up into (3) >3 km of first purple, then grey and black shales and turbidites (Schermerhorn 1975; Allen 2000).

Plutonic rocks of similar composition to the volcanic rocks are found in the northern part of the IPB, in a zone that probably represents the roots of the thrust complex.

The IPB has regional-scale, weak to moderate hydrothermal alteration (attributed to seafloor metamorphism) and local strong quartz–sericite and chlorite alteration zones related to VMS mineralization. The VMS deposits typically occur in grey-black mudstones, above, or intercalated with the felsic volcanic rocks. In the southern part of the belt, the VMS deposits are seafloor-type deposits and fossil control indicates that they formed at the same time (Upper Strunian) over an extensive area. In the northern part of the belt, the deposits are interpreted to have formed by replacement of mainly felsic volcanic rocks.

Abitibi

The Archaean Abitibi greenstone belt (Fig. 9) is approximately 500 × 200 km in size and origin-

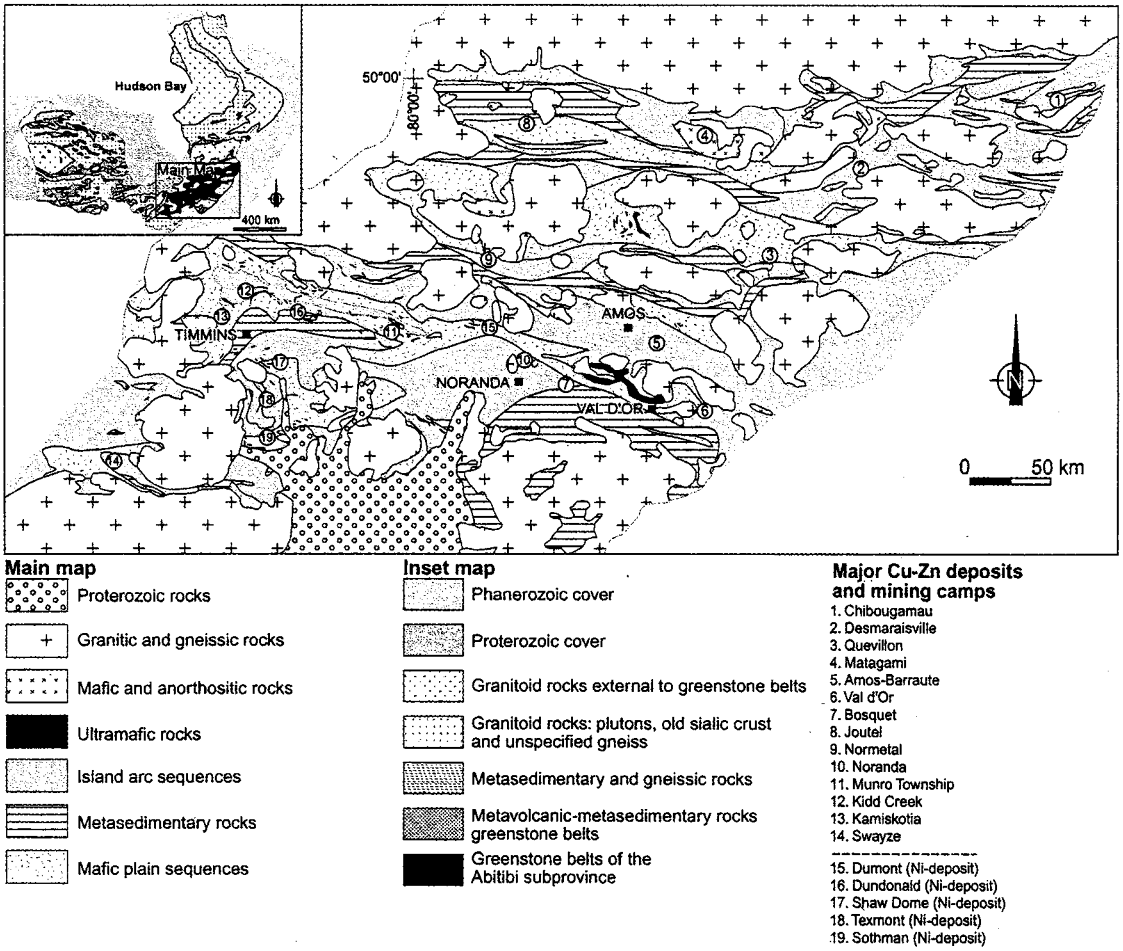

Fig. 9. Summary geological map of the Abitibi VMS district. Modified from Hannington *et al.* (1999).

ally contained over 675 Mt of volcanic-associated massive sulphide. Most VMS deposits are associated with bimodal volcanic successions dominated by tholeiitic and komatiitic basalts, and tholeiitic–calc alkaline, high silica rhyolites (Barrie *et al.* 1993; Prior *et al.* 1999*a*; Barrett & MacLean 1999). The VMS deposits mainly occur in successions that contain over 150 m of felsic volcanic rocks.

The mineralized successions can be divided into three types: (1) bimodal, tholeiitic basalt–andesite and high silica rhyolite successions that are host to more than 50% of the VMS deposits by tonnage, but comprise only 10% of the areal distribution of volcanic rocks, (2) bimodal, transitional tholeiitic to calc-alkaline andesite and rhyolite successions that are host to about 30% of the VMS deposits by tonnage but again comprise only 10% of the areal distribution of volcanic rocks and (3) a minor calc-alkaline andesite–rhyolite assemblage that is host to only one deposit (Selbaie). Barren volcanic assemblages include calc-alkaline basaltic andesite to rhyodacite and mafic to felsic alkalic volcanic rocks.

The different assemblages are interpreted to have formed in different tectonic settings. The first group is interpreted to have formed in thickened oceanic rift suites, similar to the Galapagos spreading centre or the Iceland rift zones. The rhyolites are thought to have formed by partial melting of mafic crust, reflecting high heat flow or mantle plumes (Barrie *et al.* 1993; Prior *et al.* 1999*b*). The second group is similar to rifted island arcs (e.g. Hokuroku) and the third group may be comparable to continental arc suites.

The mafic volcanic rocks are mainly lava flows and the felsic rocks include subaqueous mass flow units of pyroclastic debris, and lava flows and domes, including their autoclastic facies (de Rosen-Spence *et al.* 1980; Dimroth 1982). The VMS deposits are interpreted to have formed in proximal volcanic settings in mainly deep water environments. They are commonly associated with rhyolite domes, even though domes form a minor part of the successions. The deposits include both seafloor and sub-seafloor types (Kerr & Gibson 1993; Galley *et al.* 1996) and generally have strong chlorite and sericite footwall alteration zones (Riverin & Hodgson 1980; Barrett *et al.* 1991). Many of the deposits have at least a spatial association with mafic and/or felsic subvolcanic intrusions. The Rouyn–Noranda VMS camp, one of the best studied areas, is interpreted as a large shield volcano with a large central cauldron (Gibson & Watkinson 1990). Most VMS deposits occur above syn-volcanic faults within the cauldron.

Lau and Manus Basins

The Lau and Manus Basins are modern intra-oceanic back-arc basins in which sea floor sulphide deposits have recently been discovered (Hawkins 1995; Binns & Scott 1993; Fouquet *et al.* 1993). These basins are included in the Global VMS research project to facilitate comparisons between ancient and modern VMS mineralization. The Lau and Manus Basins are especially relevant to understanding the settings of major ancient VMS districts because these basins contain complex bimodal volcanic areas dominated by andesite, dacite and rhyolite (Vallier *et al.* 1991; Binns *et al.* 1996).

The VMS deposits are polymetallic mounds and chimney complexes that occur in proximal volcanic positions at the axis and flanks of spreading ridges (Binns & Scott 1993; Herzig *et al.* 1993; Gemmell *et al.* 1999). Several of the deposits are associated with andesitic and dacitic volcanic centres at these spreading ridges. Water depths at the sites of the VMS deposits range from 1650–2500 m, and active research is in progress to sample the volcanic host rocks, the sulphide bodies and the hydrothermal fluids that are forming them.

Tectonic setting

From these summary descriptions of VMS districts and the consensus view at the Hobart workshop, we conclude that all major VMS districts relate to major crustal extension resulting in graben subsidence, marine transgression, development of local or widespread deep marine environments, and injection of mantle-derived mafic magma into the crust (Fig. 2 and Table 1). The tectonic setting is largely confined to extensional basins near convergent plate margins, commonly in a general back-arc setting. This contrasts with many of the modern systems studied, which occur at mid-ocean spreading ridges. Back-arc to intra-arc rifts and pull-apart basin settings such as the Miocene Japan arc-back arc system and the modern Okinawa trough and Lau and Manus Basins probably provide the nearest young analogues of the settings of major Proterozoic and Phanerozoic world-class VMS districts. However, several VMS districts (e.g. Bergslagen, IPB,

Table 1. *Comparison of tectonic setting and stratigraphy of six Proterozoic and Palaeozoic VMS Belts (modified after Allen 2000)*

	GTB	Skell	MRV	LFB	Berg	IPB
Deep graben subsidence → marine incursion	✔	✔	✔	✔	✔	✔
Thick, complex volcanic stratigraphy	✔	✔	✔	✔	✔	X
'Arc-like' volcanic compositions and architecture	✔X	✔X	X	X	X	X
Continental basement	✔	?	✔	✔	? ✔	✔
Mature arc basement	✔X	? ✔	X	X	X	X
Volcanic arc nearby (<200 km)	✔	✔	X	X	X	X
Plate margin nearby (<500 km)	✔	✔	✔	✔	?	✔
Regional stratigraphic marker horizons	X	X	X	X	✔X	✔
Extensive platform/shelf facies	X	X	X	✔	✔	✔
Coincidence of mantle-derived mafic and crustal-derived felsic magmas	✔	? ✔	✔	✔	✔	✔
Bimodal volcanism regionally dominant	X	X	✔X	✔X	✔	✔
Ores mostly related to bimodal interval	✔	✔X	X	✔	✔	X
Small (S) or large volume (L) felsic volcanic centres	S	S	L	L	L	?S
VMS mainly associated with proximal felsic volcanic facies associations	✔	✔	✔	✔	? ✔	?X
Most VMS related to specific volcano-type	✔	✔	X	✔	? ✔	X
Timing late in a magmatic-hydrothermal cycle	✔	✔	✔	✔	✔	? ✔
Pyroclastic felsic volcanism dominant	X	X	X	X	✔	X
Lava and/or shallow intrusions dominant	✔	✔	✔	✔	X	✔

GTB, Green Tuff Belt; Skell, Skellefte district; MRV, Mt Read Volcanics; LFB, Lachlan Fold Belt; Berg, Bergslagen; IPB, Iberian Pyrite Belt.

Mount Read Volcanics) do not seem to have close young analogues in terms of both tectonic setting and regional stratigraphy. The Archaean districts have similarities with some young rifted oceanic and arc terrains, but again it has not been possible to find specific very close young analogues.

In detail it seems that a variety of settings exist from extensional regions at continental margins to those associated with oceanic arcs. However, most of the world-class VMS districts have significant volumes of felsic volcanic rocks and are attributed to extensional regions associated with moderately evolved island arcs (Urals?), island arcs with continental basement, especially those that formed by the rifting of continental margins and development of limited marginal basins (Japan, Silurian stage of Lachlan Fold Belt, Bathurst?, Skellefte?) or continental margin arcs (Bergslagen?), rather than extensional regions in primitive oceanic crust. The Iberian Pyrite Belt and the Mount Read Volcanics may be examples of more complex continental margin extensional settings, in which extension and VMS mineralization occurred on a continental passive margin during, or following, collision with an arc terrane. This scenario may also be relevant to parts of the southern Urals where the giant VMS deposits occur in the latest volcanic phase, shortly after the East European continent had collided with the Urals volcanic arcs.

One key feature is that in almost all VMS districts, the actual time span for the development of all the major deposits is only a few million years or less, regardless of the time span of the enclosing volcanic succession. This short time interval of major VMS formation may result from the deposits being related to specific episodes of anomalous extension, subsidence and magmatism (Fig. 2). The overwhelming impression obtained from this appraisal is that the precise setting of the deposit (e.g. mid-ocean ridge, island-arc, continental-margin etc.) is not critical but the concurrence of a set of specific tectonic and magmatic processes related to crustal extension near a plate margin may hold the key (cf. Lentz 1998).

A criticism of recent work in ancient VMS terranes is that the determination of tectonic setting has relied too much on geochemical tectonic discrimination diagrams and too little on careful, detailed documentation of the regional stratigraphy, facies architecture, igneous petrology (including geochemistry) and structural evolution.

Critical areas that need addressing to improve understanding of the tectonic setting of VMS deposits include:

1. high resolution dating of the key tectonic, magmatic and metamorphic events;
2. detailed documentation of the stratigraphic–volcanic evolution of the host settings, especially periods of extension;
3. palinspastic reconstruction of the facies architecture of ancient VMS belts;
4. integrated, detailed studies of stratigraphy, igneous petrology and igneous geochemistry so that the evolution of magmatic suites, changes from one magmatic suite to another, and changes in geochemical affinity can be tied to stratigraphy and tectonic evolution.

Volcanic facies

All of the major VMS districts show a coincidence of felsic and mafic volcanic rocks in the stratigraphic intervals that host the major ore deposits, regardless of whether the whole province is dominated by mafic, intermediate or felsic rocks. Furthermore, the VMS districts are characterized by an anomalous combination of abundant felsic rocks and widespread relatively deep marine environments compared with broadly similar tectonic settings that do not host a major VMS district (e.g. compared with most mature oceanic volcanic arcs and continental margin arcs). In this respect the major VMS districts are not typical volcanic arcs, but reflect an important dramatic extensional tectonic–magmatic event superimposed on an arc or other type of plate margin. Examples at two extremes of the spectrum of settings are Bergslagen, which is a major thick rhyolitic magmatic province that anomalously maintained subaqueous depositional environments throughout most of its development, and the Archaean Abitibi belt, which is a dominantly oceanic terrane, but the deposits themselves are associated with local thick rhyolite sequences.

The mafic rocks most closely associated with the VMS deposits are mantle-derived basalts and basaltic andesites. They are generally tholeiitic or transitional in affinity, although in the Silurian Cowombat rift of southeastern Australia they are part of a mantle-derived calc-alkaline basalt–andesite–dacite suite (Stolz *et al.* 1997). The felsic volcanic rocks associated with the major VMS deposits are calc-alkaline or tholeiitic dacite–rhyolite and are mainly interpreted to have been derived by crustal melting (Fig. 2). Intermediate andesite–dacite suites are abundant in some of the VMS regions, but they are not preferentially associated with the major VMS deposits. Consequently, it is not possible to generalize that specific magma compositions or affinities are preferentially related to major VMS deposits world-wide, although this may be the case in individual VMS districts. However, the coincidence in time and space of felsic volcanism and mantle-derived mafic magma (in an extensional marine basin) appears critical.

Understanding the facies architecture of the host rocks is a key to understanding the setting in which the VMS deposits formed. In most districts (with the possible exception of parts of the IPB), the major VMS deposits occur within or adjacent to proximal (near-vent) rhyolitic facies associations. Submarine rhyolite dome complexes with associated pyroclastic facies are probably the most common host volcano type (Hokuroku, Skellefte, Abitibi, Silurian successions in the Lachlan Fold Belt). However, calderas dominated by rhyolitic pyroclastic facies or lava flows are also an important host (Rosebery–Hercules in the Mount Read Volcanics, Bathurst?, Noranda). Individual dome volcanoes that host VMS deposits may generally be components of larger multi-vent volcanoes or volcanic systems. However, these larger volcanic systems are at present generally poorly defined and understood. An exception is the Rouyn–Noranda VMS camp where mapping shows that rhyolite dome complexes are components of a large shield volcano and cauldron (Gibson & Watkinson 1990).

Volcaniclastic rocks are abundant in the host sequences to VMS deposits and are generally diagenetically and hydrothermally altered, and in the case of ancient terranes, also deformed and metamorphosed. Consequently, primary rock textures are partly obscured and it is no simple matter to map and interpret the origin of the rocks. Until recently, most clastic felsic volcanic rocks were assumed to be pyroclastic rocks. However, recent studies show that in many VMS districts, the abundance of pyroclastic rocks has been greatly overestimated and that many of the apparent clastic rocks are hyaloclastites, autobreccias, debris flow deposits, and even altered coherent lavas, all generated by non-explosive fragmentation mechanisms (de Rosen-Spence *et al.* 1980; Yamagishi 1987; Allen 1988). Furthermore, there is no guarantee that thick beds of pyroclastic debris in marine basins were erupted locally within the deep water part of the basin. In many cases these beds are subaqueous mass flow deposits of pyroclastic debris transported into deep water environments from subaerial and shallow-water vents (e.g. significant parts of the Mount Read Volcanics and Green Tuff successions). However, locally erupted felsic submarine pyroclastic rocks are still regarded as abundant (Bathurst) or locally abundant (Mount Read Volcanics, Green Tuff) in some VMS districts. The details of these submarine pyroclastic eruptions, such as the location of vents, water depths of the vent areas, eruption styles and mechanisms, and relationship to evolution of the magmatic and hydrothermal system, have rarely been carefully documented. Large pyroclastic caldera volcanoes were proposed in the 1970–80's as the host to many VMS districts (e.g. Ohmoto 1978). However, several of those interpretations were partly based on the superficial circular shape of some mining districts (Bathurst, Hokuroku), now known to be an artefact of younger deformation and the position of cover sequences, and partly to the erroneous interpretation that most felsic volcaniclastic rocks are pyroclastic deposits.

Volcaniclastic rocks are also significant in that a simple plot of large tonnage ore bodies against volumes of volcaniclastic rocks shows a correlation, which suggests a causal relationship (H. Gibson, 2000 Hobart workshop presentation). Volcaniclastic sequences appear to promote formation of massive sulphides by infiltration and replacement below the sea floor; a situation that may trap more of the total metal budget. In volcanic sequences dominated by lava flows and intrusions, most VMS ores form at the sea floor and more of the metal budget might potentially become dispersed from hydrothermal vents into the basin waters.

In addition to being located in proximal volcanic facies, most major VMS deposits show evidence of having formed at a particular stage in the evolution of the enclosing volcanic succession. In many VMS districts the main VMS deposits are concentrated at the top, or in the upper part of the major syn-rift felsic volcanic unit (IPB, Green Tuff belt, Skellefte, Mount Read Volcanics, Silurian SE Australia, Bergslagen, Bathurst). Horikoshi (1969) also showed that at the more local scale, each of the Kuroko deposits of the Kosaka area in the Hokuroku district, formed at the end of a specific rhyolite volcano cycle, comprising (1) extrusion of large domes and flows, accompanied by pyroclastic eruptions of gas-rich magma, (2) continued extrusion and intrusion of degassed magma to form smaller domes and cryptodomes, (3) small phreatic ('steam') eruptions from the lava domes, followed by (4) effusion of ore solutions to the sea floor to form massive sulphides. This volcanic cycle is analogous to the classic subaerial dome eruption cycle (see Cole 1970). Other VMS deposits have also been shown to be preferentially associated with the late stage of evolution of specific rhyolite volcanoes (e.g. Allen *et al.* 1996*b*). Furthermore, the VMS deposits and their host rhyolite volcanoes are commonly followed by a significant change in the pattern, composition and intensity of volcanism and sedimentation, especially a pause in felsic volcanism, deposition of mudstone, and fissure eruption of mantle-derived basalts (Mount Read Volcanics, Silurian SE Australia, Skellefte, Green Tuff belt, Abitibi, Bathurst, Bergslagen). These basalts commonly form the mafic component of the coincident felsic and mafic volcanism related to VMS deposits.

The formation of many major VMS deposits at specific stratigraphic positions, and at specific stages in the evolution of individual rhyolite volcanoes indicate that either the felsic magmatic–hydrothermal cycle (and it's interplay with mafic magmatism) creates and focuses an important part of the ore solution, or that specific types of volcanism focus when and where a metal-bearing geothermal solution can be concentrated and expelled to the sea floor, or both. A major challenge now is to determine which of these possibilities is correct and why, and to determine in what way these links are recorded in the regional tectonic–volcanic evolution of the basin, and evolution of the hydrothermal system. These are major aims of the Global VMS research project.

Critical areas that need addressing include:

1. the need for more facies mapping in VMS districts to build up models of volcanic facies architecture, volcanic evolution and palaeoenvironment;
2. what is the connection between the position of VMS deposits in the evolutionary cycle of their host volcanoes and the position of the deposits in the regional tectonic and basin evolution and what are the common features from district to district;
3. can the stratigraphic position (ore horizon) of VMS deposits be recognized in the regional stratigraphy away from known ore deposits, and if so, how;
4. the role of basalts in the evolution of the felsic volcanoes that host VMS deposits and in the formation of the VMS deposits themselves;

Structure

The VMS belts and ore deposits under consideration span an enormous range in style and degree of deformation and metamorphism. Most of the successions, except the modern Pacific basins, the young Green Tuff belt and parts of the Archaean Abitibi, are strongly deformed. Fold-thrust belt type deformation patterns are particularly common. A likely explanation for this deformation is that VMS districts are mainly related to extensional basins near plate margins, and these basin successions generally become inverted and strongly deformed during the inevitable closure of the basins. Basin closure probably in most cases results from arc–arc, arc–continent, or continent–continent collision at the plate margin.

Despite the extent of deformation in most VMS districts and the important role of structural studies in unravelling the stratigraphic successions, the amount of detailed, high-quality structural work that has been carried out varies greatly. Problems include the difficulty in carrying out structural analysis in complex volcanic successions without prominent marker units and the paucity of structural geologists with experience of volcanic stratigraphy. However, some districts have been the focus of excellent structural studies that have demonstrated their use in understanding the geological evolution of the district and in ore discovery (Bathurst, Mount Read Volcanics). In the late 1980s and early 1990s the Mount Read Volcanics were the focus of a government regional mapping campaign, and this work has greatly increased the knowledge of the district and laid the foundation for subsequent research studies and mineral exploration. In contrast, the intensely deformed Bergslagen district is just now receiving its first modern regional structural interpretation. In the strongly deformed and glacial sediment covered Skellefte district, electrical geophysical exploration methods have until recently had enormous success in locating ores. This success has contributed to the generally poor knowledge of regional stratigraphy and structure. The recent success of gravity surveys in locating large ore bodies in the IPB has to some extent also retarded studies of stratigraphy and structure in the IPB, despite the fact that the IPB has enormous potential for the discovery of blind ore bodies in fold–thrust structures.

It can be concluded that good quality regional mapping of stratigraphy and structure is required in order to make meaningful interpretations of regional basin evolution and the setting of VMS ores, and for a foundation for local detailed research projects.

Critical areas that need addressing include:

1. integrated mapping and research studies of volcanic stratigraphy and structure at the regional and ore deposit scale.

Ore deposit characteristics

Despite the criticism that in-depth ore deposit studies are just collecting data, it is acknowledged that very few modern detailed accounts of VMS deposits and districts have been published. Furthermore, such studies provide the integrated data sets on which realistic detailed interpretation can be based. Recent studies have been made on the Noranda, Kidd Creek and Bathurst districts. The Urals has a great deal of primary data in Russian that is in need of compilation. Regional facies mapping has commenced in the Skellefte and Bergslagen districts, but comprehensive modern descriptions of the ore deposits are lacking. Detailed ore deposit descriptions and facies mapping are advanced in parts of the Mount Read Volcanics, but are not yet sufficient to make correlations between ore deposit characteristics, volcanic setting, depositional environment and basin evolution. Recent work in several VMS districts suggests that there are relationships between the facies architecture of the host volcanic succession (lava pile, lithic volcaniclastic rocks, pumiceous volcaniclastic rocks) and the style (sea floor exhalative, subsea-floor replacement), shape (mound, sheet, multiple lenses or tongues) and size of VMS deposits. However, these relationships have not been explored in detail.

Many VMS districts have numerous small–medium sized deposits and just one or two giants (e.g. Abitibi–85 deposits around 1 to 2 million tonnes, Kidd Creek and Horne around 100 Mt; Skellefte–over 80 deposits, the 52 largest have a median size of 1 million tonnes, and only Kristineberg and Rakkejaur are over 20 Mt). However, the largest deposits are often not the richest (e.g. Skellefte, Mount Read Volcanics). Studies should focus on large, well-exposed deposits and the smaller rich deposits so that the characteristics of the most economically viable deposits are fully documented. Compilations of the settings and characteristics of small deposits and low value deposits are a second priority but are also important for the purposes of comparison.

Critical areas that need addressing include:

1 more high quality, integrated, multi-disciplinary studies of major VMS deposits;
2 a better descriptive classification of the styles (types) of massive sulphide deposits;
3 improved criteria for the genetic classification of deposit types–current nomenclature is too rigid and is based on limited data;
4 investigation of the relationships between host stratigraphy (facies architecture) and the style (geometry, seafloor versus subsea-floor position, size, metal zonation) of VMS deposits;
5 more information on the mineralogy and ore mineral textures of deposits (e.g. a database on mineral textures) complemented by modern chemical and isotopic studies;
6 fluid-inclusion data and other information on the salinity of ore fluids, fluid compositions, fluid sources, pathways and effects such as alteration and ore mineral deposition;
7 modelling of fluid-rock reactions in VMS hydrothermal systems.

Exhalites

Some VMS districts have prominent sulphide or oxide facies exhalites that mark the ore-horizon away from the deposit (e.g. Bathurst, Noranda), whilst others do not (Mount Read Volcanics, Skellefte). There remains uncertainty about which are true hydrothermal exhalites, which may relate to higher than average heat-flow, which are reworked clastic weathering products and which are regional weathering phenomena of volcanic rocks. Some VMS deposits, such as sub-sea floor replacement deposits, may possibly have no sea-floor expression. However, this seems difficult to envisage, as the hydrothermal fluid has to escape from the mineralizing system somewhere.

An excellent database has been constructed for the Bathurst exhalites and documents extensive iron-formations of both volcanic-association (Algoma-type) and possibly starved sediment sources (Superior-type). However, some other districts that have prominent chemical sediment units and exhalites, such as Bergslagen, have no modern, systematic, comprehensive data on these rocks.

Critical areas that need addressing include:

1 how to recognize exhalites in the field and are exhalites, or the chemical and mineralogical changes resulting from their interaction with the sea floor substrate, common in VMS districts but largely unrecognized;
2 a compilation of exhalite mineralogy and geochemistry in several VMS districts;
3 how to distinguish exhalites related to VMS mineralizing systems from other exhalites (e.g. iron formations) not related to VMS systems;
4 the possibility that some iron formations in VMS camps may not be exhalites–e.g. Bergslagen;
5 the reasons why some exhalites extend beyond the sulphide deposit whereas others do not.

Mineralogy, metal zonation and alteration

The chemistry of the footwall volcanic rocks appears to be the biggest control on the mineralogy of the ore deposits. This may simply reflect the mineralogy of the volcanic rocks that are leached during hydrothermal alteration, e.g. break-

Table 2. *Relationships between the composition of massive sulphide mineralization, host rock type and tectonic setting, suggested from exploration of the modern sea floor*

	Pb, As, Sb, Au			
	Very high	High	Low	Absent
Setting	Continental back arc	Oceanic back arc	Sedimented mid-ocean ridge	Sediment free mid-ocean ridge
Host rocks	Rhyolite/dacite	Dacite/andesite	Turbidite sequences, MORB	MORB
Examples	Okinawa Trough	Lau and Manus basins	Mid-ocean ridges	Mid-ocean ridges

down of mafic minerals–copper and zinc, breakdown of felsic minerals–lead, barium etc. However, some workers attribute part of the metal composition of the ore deposits to primary magmatic contributions to the hydrothermal solution (Urabe 1987).). Exploration of the modern sea floor suggests the relationships shown in Table 2 between the composition of VMS ores, host rock type and tectonic setting:

Exploration of the modern sea floor suggests the relationships shown in Table 2 between the composition of VMS ores, host rock type and tectonic setting.

Metal zonation appears to be largely related to the temperature of the hydrothermal system within the actively forming VMS deposit, and the pattern of temperature decrease between the high temperature core of the deposit and the low temperature margins (e.g. high temperature–copper, low temperature–zinc, lead, barium). Metal zonation may be complicated by changes in the hydrothermal fluid flow pattern and temperature gradients with time.

Several factors (e.g. rock composition, temperature, fluid composition, salinity) affect hydrothermal alteration mineralogy; but fluid pH appears to have the largest effect. At very low pH (below 3.5), kaolinite and pyrophyllite become the stable phases instead of muscovite. Footwall rocks provide the buffer to fluid chemistry. Low pH fluids might indicate a closer association with a magmatic source, i.e. fluids more out of equilibrium with wall-rocks. The mineralogy of ores, gangue minerals and footwall alteration could be used better to help interpret the evolution of VMS deposits. Lithogeochemistry can be used to map out chemical zonations and mass changes in the host succession caused by hydrothermal alteration, and to locate the main hydrothermal conduits (upflow zones) and recharge zones (Barrett *et al.* 1991; Barrett & MacLean 1999). New ideas of the complex electro-chemical interaction between oxidized seawater, precipitated sulphide assemblages and the volcano-sedimentary host rocks could help to explain some of the variations in deposits seen in ancient systems.

Critical areas that need addressing include:

1 systematic data on the mineral chemistry of ore and alteration minerals at a selection of different VMS deposit types;
2 correlate chemistry of alteration minerals with whole rock geochemistry and volcanic-sedimentary facies;
3 synthesis of the geometry, mineralogical zonation and chemical zonation of hydrothermal alteration (footwall and hanging-wall) at a range of different types of VMS deposits.

The way forward

The discussion above provides a summary and some highlights of the GEODE VMS database and the Hobart workshop. This also chronicles the background and birth of a global VMS research project. The ultimate scope and success of the project depends on the enthusiasm and imagination of the research teams and the level of funding that can be achieved. We are now organizing the main research stage of the project to answer some of the important scientific questions raised above, and to address the following general objectives.

(1) Create an international network of experienced researchers with a range of different skills and develop a collaborative international research programme in which research teams work on common goals and with significant exchange of researchers, skills, ideas and data (Fig. 10). The project plan includes teams with scientists from seven European nations (Sweden, Germany, Spain, Portugal, United Kingdom, France, Switzerland) and a Russian, Canadian, Australian, Japanese and possibly an Andean-Swiss team.

(2) Using an integrated multi-disciplinary approach, determine how mineralization, volcanic evolution, and extensional tectonic evolution are interrelated in a number of world-class VMS

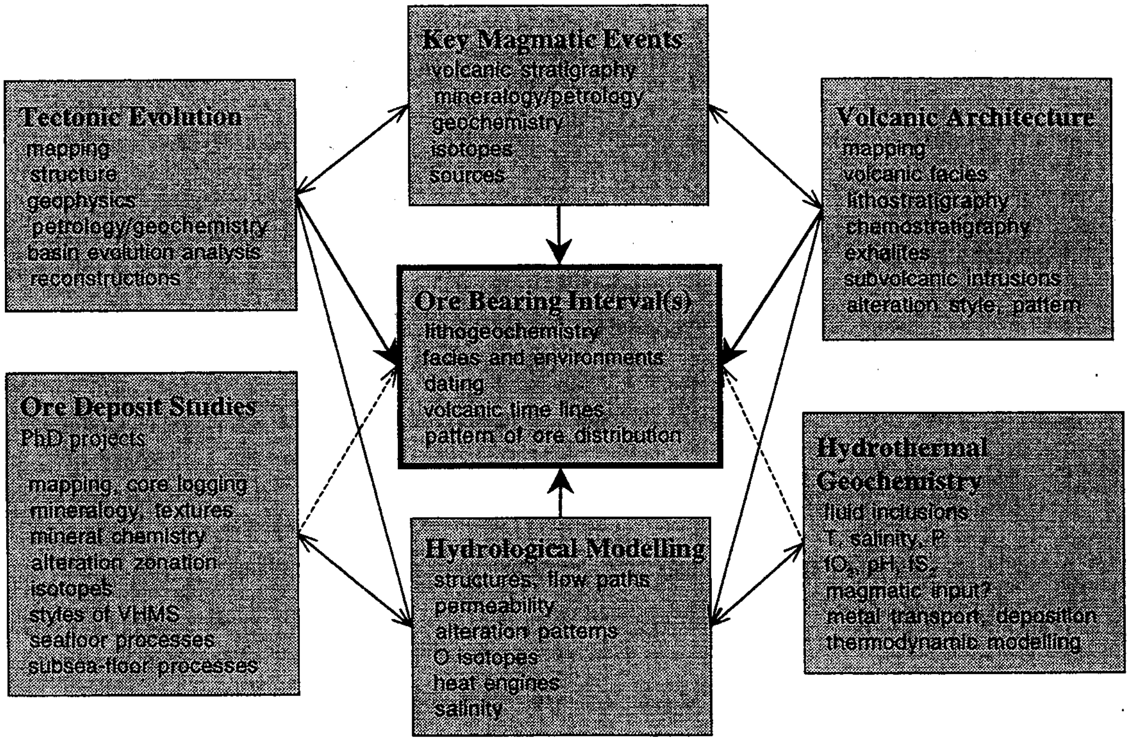

Fig. 10. Framework for the integration of component studies of the Global VMS research project.

districts. Field-oriented research (stratigraphy, volcanology, structural geology) will be integrated with laboratory studies (petrology, geochemistry, isotope geochemistry, analysis of geophysical data) as illustrated in Figure 10. Mining districts under consideration for inclusion in the project include Skellefte and Bergslagen districts, Sweden, Southern Urals, Russia, Iberian Pyrite Belt, Spain and Portugal, Mount Read Volcanics, Australia, Bathurst, Abitibi and Flin Flon districts, Canada, the Andean Belt, South America, Green Tuff belt, Japan and Manus and Lau Basins, Pacific Ocean (Fig. 1).

(3) Develop criteria to recognize these relationships in the field so that it becomes possible to identify the volcanic intervals that are likely to host major ore deposits in any given district.

(4) Organize and guide the studies in the various mining districts and bring them together in a global synthesis. Specifically, compare and contrast the results from each district and thereby distinguish those features that are essential to formation of world-class ore deposits (i.e. occur in all districts), from those that are not essential but are locally important (i.e. occur only in specific districts).

In this paper we have synthesized data, ideas and suggestions from many colleagues, especially scientists in the Global VMS research teams. We wish to thank all these colleagues for the great spirit of collaboration that forms the core of the project. Rod Allen and Pär Weihed also thank the Research Institute of Materials and Resources (RIMR) at Akita University, Japan, the Centre for Applied Ore Geology Studies (CTMG) at Luleå University of Technology, Sweden, the European Science Foundation programme for Geodynamics and Ore Deposit Evolution (GEODE) and the GEORANGE research programme, Sweden for supporting this work.

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