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The Quiet Counter-Revolution: Structural Control of Syngenetic Deposits

JoAnne Nelson

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Article abstract

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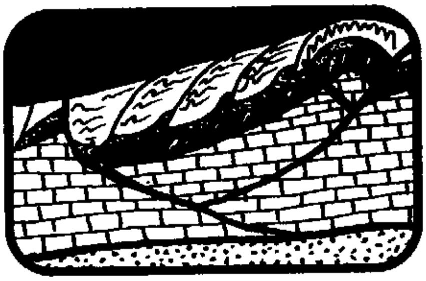


The Quiet Counter-Revolution: Structural Control of Syngenetic Deposits

JoAnne Nelson
British Columbia Geological Survey
Box 9320 Stn. Prov. Govt.
Victoria, British Columbia V8V 1X4

SUMMARY

Syngenetic massive sulphide deposits, defined as sea-floor accumulations of sulphide minerals along with their enclosing strata, produce most of Canada's lead and zinc, as well as significant amounts of copper and precious metals. Their definition as a class has come about during the last 40 years, at the expense of earlier models that defined them as structurally controlled replacement deposits. This redefinition led to a shift in emphasis to observed stratigraphic as opposed to structural features; in some cases, syngenetic advocates even dismissed local structural control as coincidental.

Two recent research developments have enhanced our understanding of syngenetic deposits in deformed belts. First is the volume and quality of data now available on modern sea-floor hydrothermal systems in a wide variety of tectonic settings, from the Middle Valley of the Juan de Fuca Ridge to the back-arc basins of the western Pacific, and in particular Kuroko (rifted arc) analogues, which previously were poorly studied compared to mid-ocean ridge and continental rift examples. Second is the concept and study of inverted basins: the mechanisms by which normal fault-bounded basins are deformed during later crustal compression, and the peculiar structural geometries that result. Present investigations of syngenetic deposits now evaluate equally their stratigraphic setting — the "ore horizon" concept — and the primary and reactivated structures that controlled their origins.

RÉSUMÉ

Les gisements de sulfures massifs syngénétiques et qui sont définis comme étant le résultat de l'accumulation de minéraux sulfureux sur les fonds océaniques et dans les couches environnantes, constituent la source principale du plomb et du zinc produits au Canada ainsi qu'une proportion importante du cuivre et des métaux précieux. Au cours des 40 dernières années, ce modèle s'est imposé comme une classe de gisements et a supplanté le modèle de gisement par remplacement à contrôles structuraux. Cette redéfinition explique qu'on s'intéresse maintenant surtout aux aspects stratigraphiques plutôt qu'aux aspects structuraux ; dans certains cas, les partisans du modèle syngénétique ne voient que coïncidences dans les aspects structuraux locaux.

Deux avenues de recherche récentes ont permis d'améliorer nos connaissances des gisements syngénétiques au sein des zones orogéniques. Il s'agit d'abord du volume et de la qualité des données disponibles sur les systèmes hydrothermaux modernes des fonds océaniques dans des cadres tectoniques variés, allant de la vallée médiane de la dorsale médio-océanique de Juan de Fuca, à ceux des bassins d'arrière-arc de la portion ouest du Pacifique, tel ceux du type Kuroko (arc de fosse), lesquels étaient jadis peu étudiés par rapport aux gisements de dorsale médio-océanique ou de fossé tectonique continental. Deuxièmement, le concept même de bassins inversés ainsi que les recherches à ce sujet, soit ce phénomène par lequel des bassins délimités par des failles normales sont déformés par l'action d'une compression crustale ultérieur et qui explique l'existence de caractères géométriques si particuliers qui en résultent. Les études actuelles des gisements syngéné-tiques s'intéressent autant aux aspects stratigraphiques — le concept d'horizon minéralisé — qu'aux aspects structuraux initiaux et réactivés qui en ont régi la genèse.

INTRODUCTION

Almost 50 years ago, in 1948, the Canadian Institute of Mining and Metallurgy produced a special Jubilee Volume to celebrate its 50th anniversary. Entitled *Structural Geology of Canadian Ore Deposits*, the volume embodied the consensus of the day, summarized in the preface that it was "well known that the location, form and extent of ore deposits are largely controlled by the structure of the rocks in which they were deposited." Less than ten years later this assurance began to be eroded, and in twenty years it was swept away by a revolution in economic geology that redefined a whole class of massive sulphide bodies as syngenetic accumulations, stratigraphically controlled, laid down along with their enclosing volcanic and sedimentary hosts. Cordilleran deposits treated in the Jubilee Volume that now are firmly lodged in syngenetic classifications include the Britannia Mine (Irvine, 1948), Tulsequah Chief (Smith, 1948), and Sullivan Mine (Swanson and Gunning, 1948).

No revolution occurs instantaneously. A review of the literature shows some very early voices advocating syngenetic origins; and conversely, through the 1960s and even later, certain deposits were still being described as structurally controlled, which now are generally accepted to be stratabound. These late structure-centered papers make interesting reading with the benefit of hindsight. In them, some field characteristics, such as the delicate sulphide banding at Sullivan, were described in terms not unlike those in current publications, but were interpreted quite differently: thin sulphide laminations were attributed to the replacement of thin-bedded siltstone, as opposed to sedimentary sulphide accumulation (Freeze, 1966). But the core of their authors' point of view is most embodied by the relative importance assigned to different lines of evidence, particularly the central role of structures. For instance Waterman (1982) began his discussion of Payne *et al.*'s 1980 reinterpretation of the Britannia Mine as a volcanogenic massive sulphide deposit with the observation that "Britannia mineralization is confined to the Britannia shear zone, which argues that ore and structure are related." In their reply, Stone and Payne (1982) downplayed this as coincidence, emphasizing instead the strong correlation between felsic volcanic rocks and sulphide mineralization.

The association of many massive sulphide deposits with major and subsidiary faults has, if anything, been re-emphasized and clarified by recent studies. The Britannia shear zone is a broad zone of intense penetrative deformation and fabric development with a history of both pre-ore and post-ore motion (Payne *et al.*, 1980; Lynch, 1991). At Tulsequah Chief, Mississippian volcanogenic massive sulphides lie next to splays of the complex southern extension of the Llewellyn fault zone. Farther north, the Llewellyn fault underwent both sinistral and dextral motion in Early Jurassic time. The Llewellyn fault presently defines the western limit of the thick arc successions of Stikinia against more dominant older pericratonic units to the west (Mihalynuk *et al.*, 1993). Given these close juxtapositions, it is no wonder that early workers viewed faults and shear zones as first-order controls on mineralization. Had the Cirque sediment-hosted lead-zinc-barite deposit of the northwestern Rocky Mountains had been discovered prior to 1950, it too would probably have appeared in the Jubilee Volume, its generation linked to the prominent thrust fault that it abuts.

This paper explores the idea that the preoccupation of the early investigators of massive sulphide deposits with structural controls was no red herring; their approach recognized a fundamental aspect of the geology of stratabound ores. Twenty-five years after the syngenetic model took mining camps and economic geology textbooks by storm, we still have structure. The kinds of structures defined and the evidence used to define them are different, but their importance to the genesis and morphology of the orebodies has not changed.

LESSONS FROM MODERN SULPHIDE DEPOSITS

Progress in the understanding of syngenetic sulphide deposits has always relied heavily on analysis of relatively young, relatively undisturbed examples such as the Kuroko districts of Japan, and the study of active modern sea-floor hydrothermal systems. The discovery of hydrothermal mineralization at the spreading axis of the Red Sea in 1965 added tremendous strength to the syngenetic model. Since then, a whole chain of discoveries of hydrothermal systems along ocean ridges, back-arc spreading centres, and, most recently, arc rifts has borne out the essential relationship of rifting and sea-floor hydrothermal activity.

The most recent compendium of these studies is in Economic Geology's *Special Issue on Sea-Floor Hydrothermal Mineralization* (Rona and Scott, 1993). Papers describing occurrences from the Mid-Atlantic Ridge, the East Pacific Rise, and the arcs and basins of the western Pacific bring out a common theme of rift basin control. In case after case, sea-floor maps show black and white smokers and sulphide mounds localized in subbasins bounded by normal faults, within or adjacent to the axial valley of the spreading centre or incipient rift. This is true for: the Tag hydrothermal field and the Snake Pit deposit on the Mid-Atlantic Ridge (Rona *et al.*, 1993; Fouquet *et al.*, 1993a); the Middle Valley of the Juan de Fuca Ridge (Goodfellow and Franklin, 1993); the Escanaba trough on the Gorda Ridge (Zierenberg *et al.*, 1993); the Woodlark basin, where spreading is propagating into the continental margin of Papua New Guinea (Binns *et al.*, 1993); the Lau basin, backarc to the Tonga arc system (Fouquet *et al.*, 1993b; Herzig *et al.*, 1993); the Jade hydrothermal field in the Okinawa trough southwest of Japan (Halbach *et al.*, 1993); the Manus basin near New Ireland (Binns and Scott, 1993); and the White

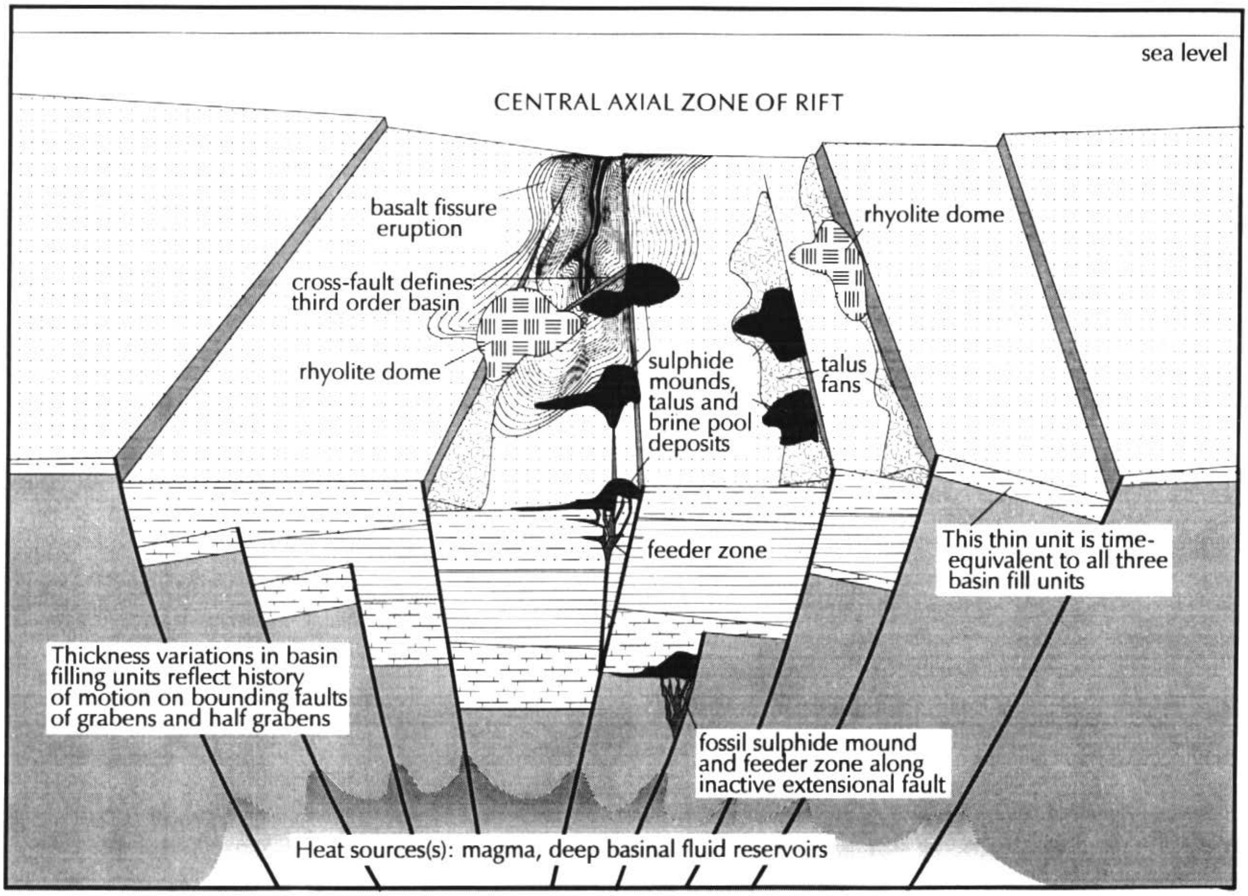


Figure 1 *Composite scenario for the setting of sea-floor hydrothermal systems and syngenetic sulphide deposits. Favored locations include the central rift zone and adjoining grabens and half-grabens, particularly along and above bounding faults and at fault intersections. The model depicted is for a Kuroko-type (arc-related) system. Without the rhyolites, and in a marginal basin environment, this would represent Cyprus-type mineralization. With no or only minor volcanic rocks present and in a submarine continental rift setting, sediment-hosted (sedex) deposits would form. Inspired by all of the papers in* Economic Geology, *v. 88, particularly Goodfellow and Franklin (1993).*

Lady hydrothermal field in the Fiji back-arc basin (Bendel *et. al.*, 1993). The southwest Pacific examples are particularily illuminating, because of their island arc or near back-arc rift locales and in some instances their associated felsic, calc-alkaline volcanism, and lead and precious metal enrichment. These correspond much more closely to onland Kuroko-type volcanogenic massive sulphide deposits than do the mid-ocean ridge occurrences.

The setting of a typical sea-floor sulphide deposit and its relationship to the faults and fault-basins of the rift valley can be summarized as follows (Fig. 1):

1) Most deposits are localized along the bounding normal faults of the main axial graben, central to the axial valley. They generally lie on the downthrown side, but they also occur on elevated fault blocks lateral to the axial graben (Snake Pit, White Lady, Middle Valley).

2) Deposits may be associated with slumps and talus debris at the foot of scarps (Tag, Lau basin).

3) In zones of propagating or incipient spreading, sulphides may accumulate on a central volcanic ridge, which later may be dissected by normal faulting (Lau basin).

4) Deposits can cluster near a discontinuity in the ridge track such as a triple ridge junction (White Lady), a transform fault offset, or a step between en-echelon segments (Jade): these areas are good candidates for localizing sub-basins and hydrothermal upflow.

The close correspondence between sulphide mounds and graben-bounding faults indicates that hydrothermal fluids are using the faults as conduits (Goodfellow and Franklin, 1993, p. 2066); on Figure 1, feeder zones are shown along the faults at depth. The vent-fault association represents a satisfying accord between observation and theoretical prediction. Fluids that carry metals, like all hydrothermal fluids, prefer the highly permable conduit that a fault can provide. The fault must be active: as minerals precipitate out, the system self-seals, so that repeated fault motion is required to keep the pipes clear.

Syn-sedimentary and/or syn-volcanic faults inform the architecture of surface units. The axial graben contains a thicker fill than the terraces that bound it, and in-

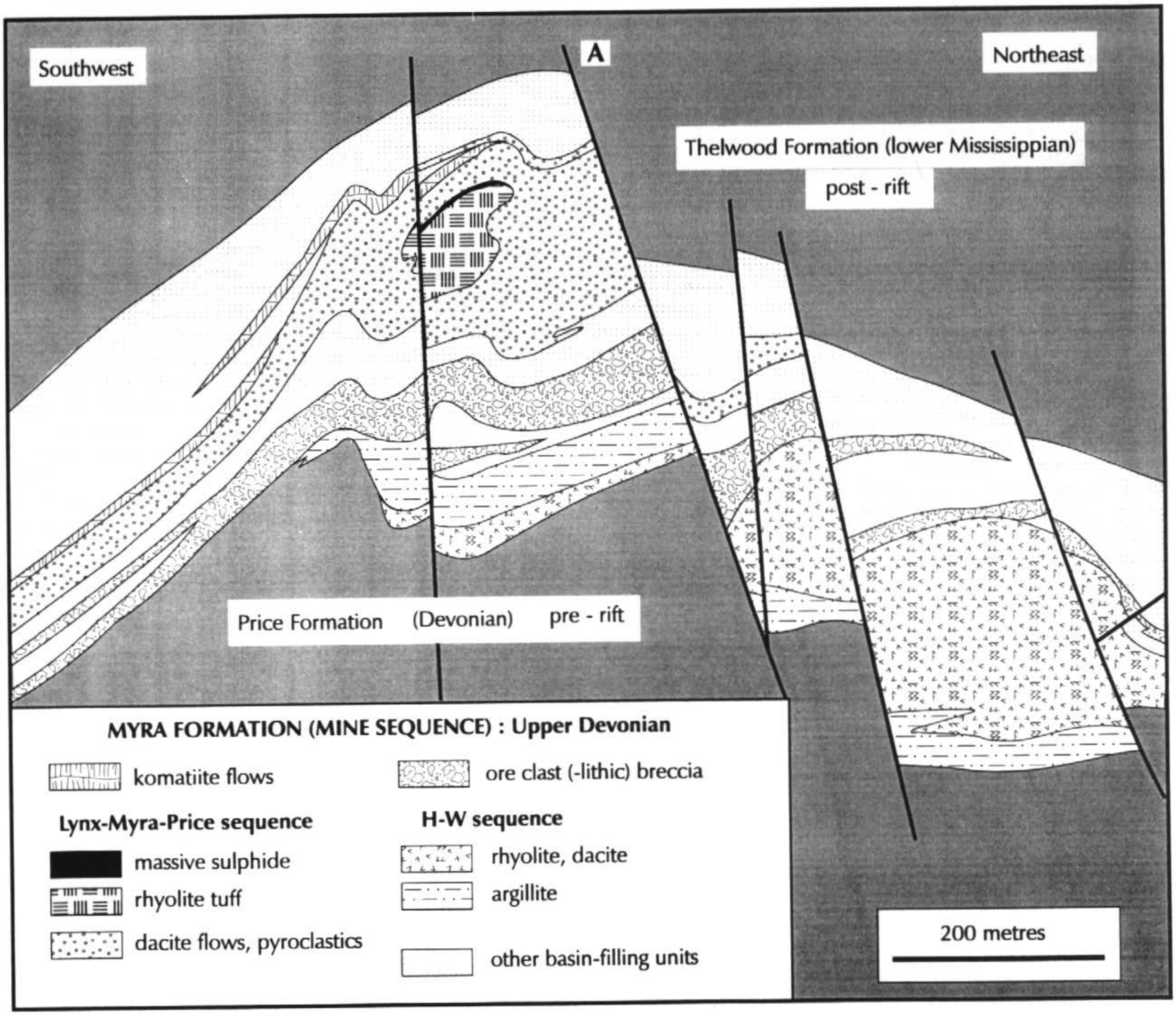


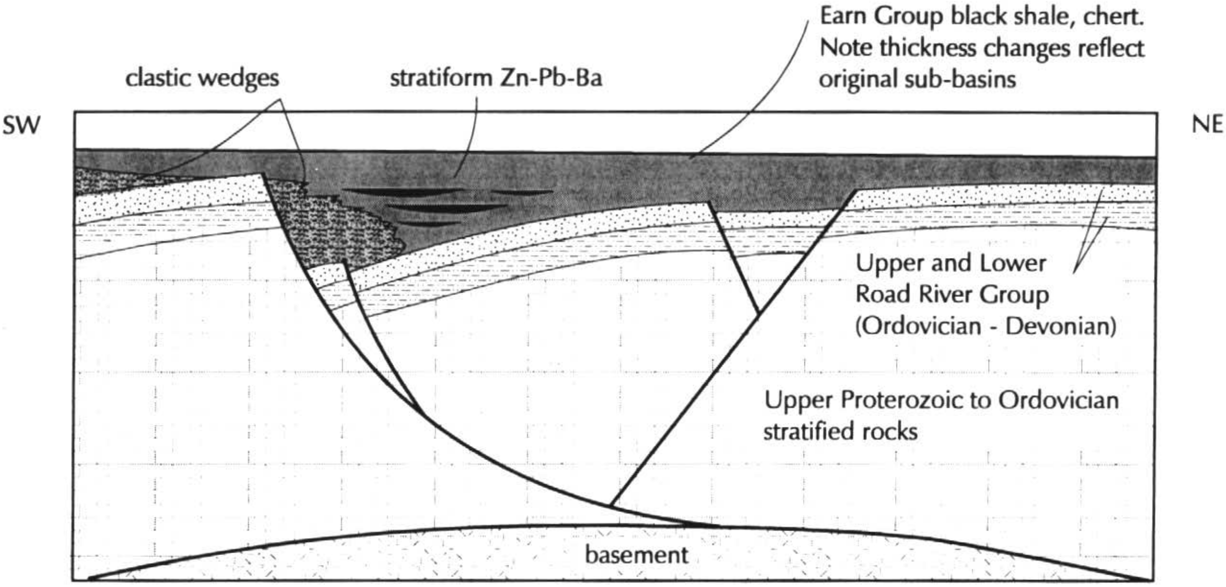
Figure 2 *Cross section of a part of the Buttle Lake mine area, through the Price zone (Juras, 1987). The fault labelled* **A** *delineates marked thickness contrasts of opposite sense in the H-W and Lynx-Myra-Price felsic volcanic/sulphide sequences. The H-W sequence thickens abruptly to the northeast, the Lynx-Myra-Price to the southwest. This fault probably had a complicated history of syndepositional motion. Restoration of the ore-clast breccia unit shows that it was southwest-side up during that interval, with a basin to the northeast. Restoration of the base of the post-rift Thelwood Formation shows southwest-side down motion. Komatiitic flows, as well as Price volcanic centres and sulphide mineralization, only occur to the southwest. Much later, Cretaceous or Early Tertiary, motion brought the southwest block up again.*

deed each normal fault in the axial region potentially marks a change in thickness and facies of sediments and epiclastic units. These stratigraphic contrasts can help in reconstructing the rift geometries associated with ancient deposits. Local turbidites, talus and debris flow breccias write the story of the scarps into the sedimentary record (Fig. 1).

APPLICATION OF RIFT MODELS TO FOSSIL DEPOSITS

In studying on-land massive sulphide deposits one has the tremendous advantage of extensive three-dimensional observation, as compared with deep ocean tools: a remote-controlled camera, geophysical remote sensing, and a few drill holes. On the other hand, the older deposits, particularly those in orogenic belts, have borne the whips and scorns of time, with

1. During basin development (Late Devonian)



2. Jura-Cretaceous shortening and inversion of the Devonian basin

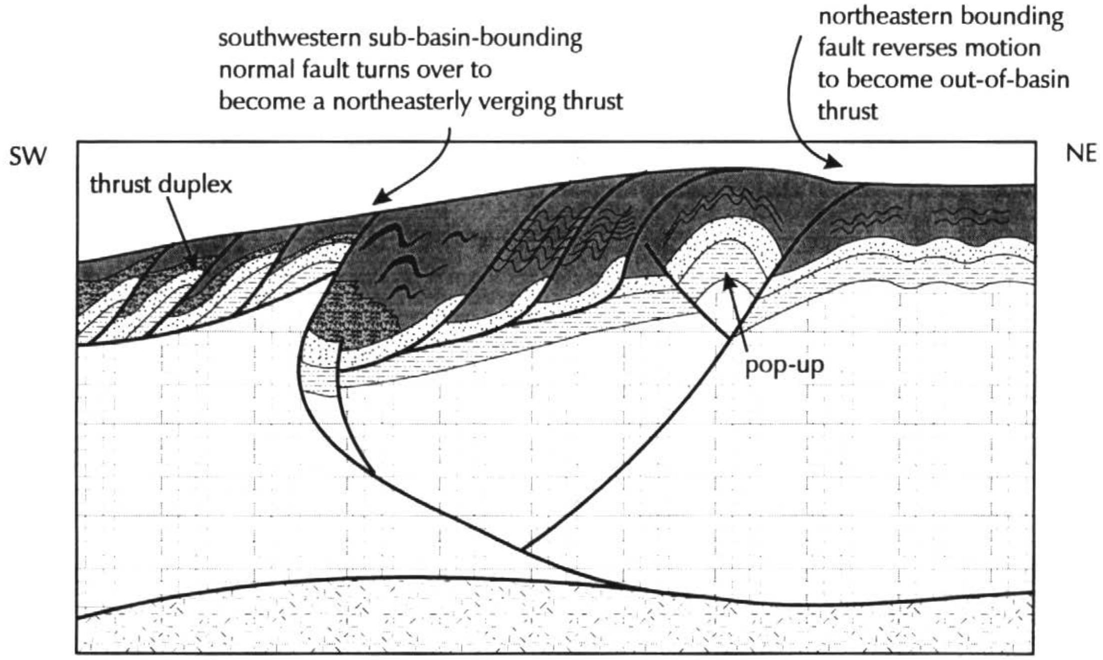


Figure 3 *Cross sections showing inversion of part of the Kechika Trough (McClay et al., 1989). In the original configuration* (**1**), *the Earn Group thickens into the centre of the rifted basin. Sediment-hosted syngenetic sulphide and barite deposits cluster near the western bounding fault. During Mesozoic northeasterly folding and thrusting* (**2**), *the basin becomes a positive structural feature. The syngenetic deposits now are located in the immediate footwall of a major thrust fault.*

their intendant obscuring of original features. The Kuroko districts of Japan provide a well-exposed, well-studied, and fairly undeformed intermediate case (Ohmoto and Skinner 1983). There, syngenetic massive sulphide mineralization occurred over a limited period of time — at most 11-16 million years ago — within a restricted, fault-bounded subsiding oceanic trough 100 km wide and >1500 km long, located within the longer-lived Late Oligocene to Miocene Green Tuff Belt, a widespread arc-rift sequence in western Japan related to the opening of the Japan Sea. There is a close temporal correlation between the mineralization, the onset of bimodal volcanism, and dramatic sinking of the trough floor from near sea level to 2000-3500 m in depth. Cathles *et al.* (1983) interpreted the tectonic/metallogenetic event as a short-lived intra-arc rift episode. In generalizing from this case, they wrote a statement that is almost prescient in its anticipation of the numerous sea-floor discoveries to come:

> ...when one seeks massive sulphide deposits, one looks basically for zones of crustal extension or rifts, for hydrothermal circulation systems driven by the intrusion of mafic (or bimodal) magmas.

The Kuroko deposits cluster in discrete districts, which are reminiscent of the sub-basins in modern rift systems: Cathles *et al.* (1983) depicted these as extensional segments joined by transform faults. On a district scale, individual deposits are controlled at least in part by secondary vertical faults. Scott (1980) pointed to the importance of pre-existing linears — reactivated basement structures — in the definition of sub-basins and sites of hydrothermal activity. Large (1983) keyed the location of sediment-hosted stratiform sulphides to third-order basins: subgrabens within axial rift zones within broad rifted provinces. Syngenetic deposits, it would seem, follow the well-known real estate adage with a further twist: structure, structure, structure.

The rock record around both volcanogenic and sediment-hosted deposits carries ample evidence of the effects of rifting. Extensive feeder zone breccias, seamed and cemented by tourmaline and sulphide minerals, form an integral part of the Proterozoic mineralization story at the Sullivan Mine (Freeze, 1966; Hamilton *et al.*, 1983). Sullivan occurs at the intersection of the regional-scale, east-west-trending Kimberley fault and a series of north-trending faults within the Sullivan–North Star Corridor, a Proterozoic rift zone and hydrothermal field (Turner *et al.*, in press a, b). Proterozoic movement on the Kimberley fault is shown by alteration, dykes and a syn-Sullivan conglomerate unit in the lower Aldridge Formation: all of these lie adjacent to the fault and parallel its trace. The north-trending faults bound coarse-clastic-filled syn-rift sub-basins.

The Devonian sedimentary exhalite deposits at Macmillan Pass, Yukon, occur near the bounding faults of a synsedimentary basin where they are intersected by cross-structures (Abbott and Turner, 1990). The Jason deposit, for instance, is texturally and mineralogically zoned with respect to a fault which is thought to have acted as a hydrothermal upflow feeder. Debris flow deposits, which are interbedded with the sulphides, thicken towards the fault; soft-sediment ductile deformation textures are developed adjacent to it, evidence for syn-sedimentary movement (Turner, 1990). Exhalative mineralization at the Driftpile sediment-hosted deposit corresponded to an abrupt shift from chert deposition to mud turbidite influx. This suggests that the hydrothermal fluids were released at the beginning of fault move-

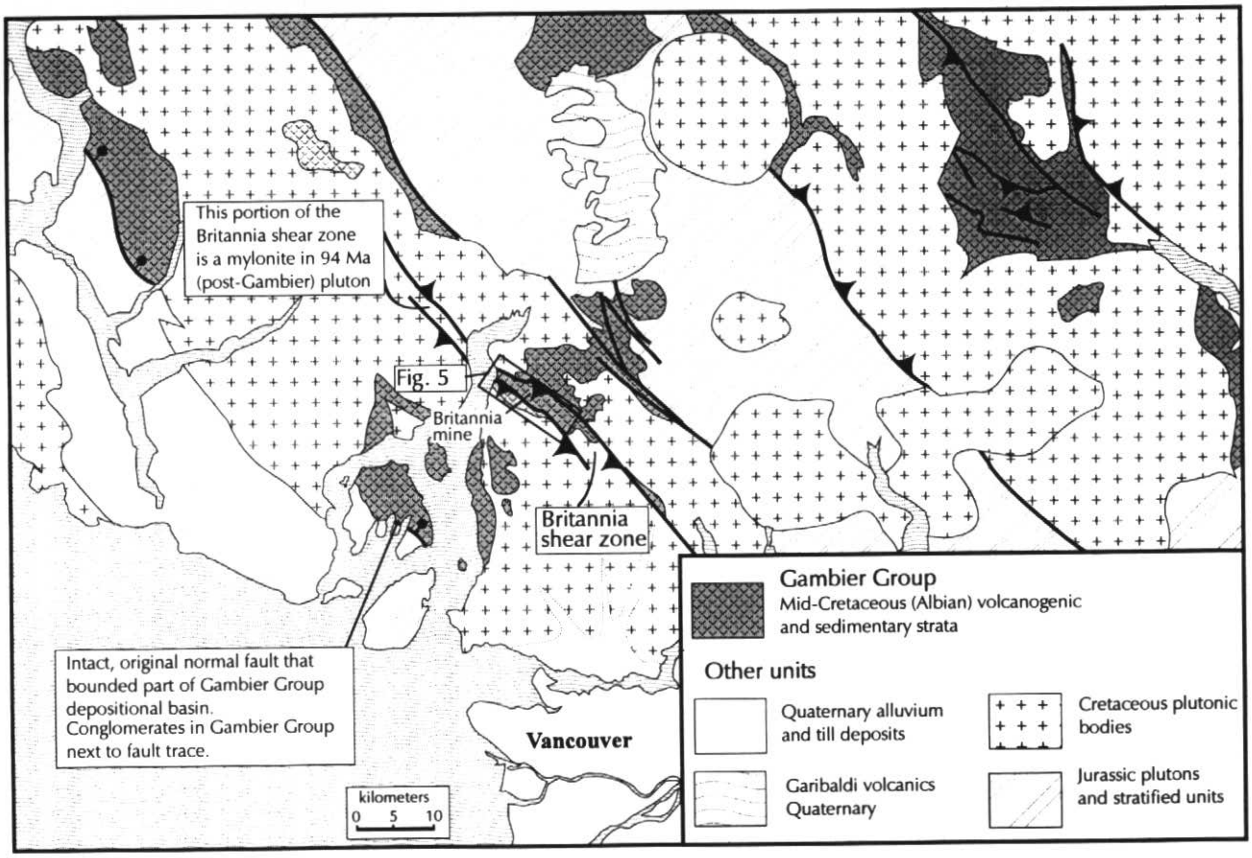


Figure 4 *Regional setting of the Britannia shear zone in the southern Coast Mountains, as one of a family of syn-Gambier Group northwesterly-striking normal faults and reactivated Late Cretaceous (96 to 84 Ma) thrust faults (Monger, 1993).*

ment, which later resulted in slumps from sea-floor scarps as absolute displacement on the faults increased (Nelson *et al.*, 1995).

The Buttle Lake Mine on Vancouver Island, hosted by the Devonian arc-related Sicker Group, is one of the Cordillera's longest-producing volcanogenic deposits, with 10 million tonnes mined since 1967. It is made up of an array of orebodies that cluster in a zone about 3 km across and 10 km long that Juras (1987) interpreted as an arc rift basin. Volcanic units of calc-alkaline, arc affinity filled the basin from the northeast, while rift tholeiitic basalts entered it from the southwest. Individual orebodies tend to be elongate parallel to the main basin, although this is not universally the case. Cross faults, and rhyolite domes competing for limited space in the graben, also exerted control on orebody morphology. In the vicinity of the ore-bodies, units thicken abruptly across faults (Fig. 2). Interestingly, near the Price orebody, some units are thicker in horsts rather than in grabens, contrary to what one might expect. Most likely, motion sense on these faults was reversed during much later Cretaceous compressional tectonics. The reversal of motion on faults, in which normal sense is succeeded by reverse displacement, is one of the key features of basin inversion: the remobilization of fault-bounded sedimentary (-vol-

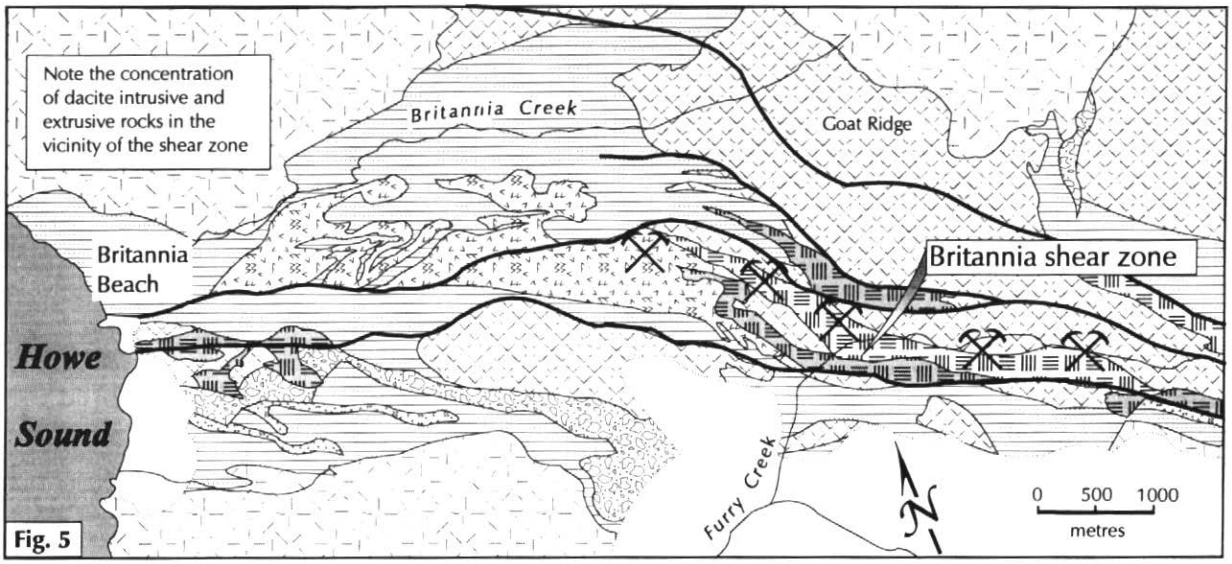
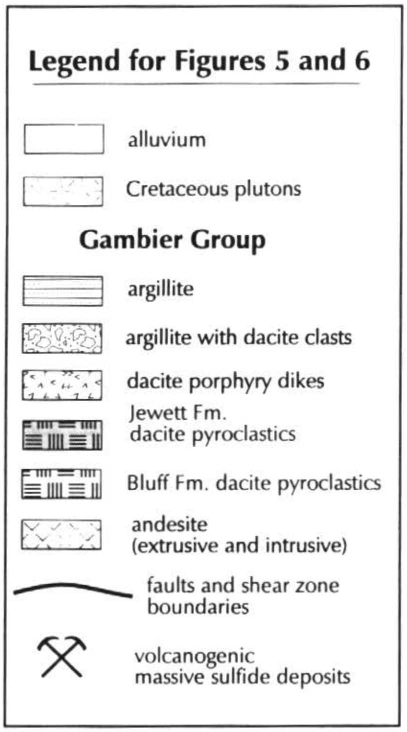


Fig. 5



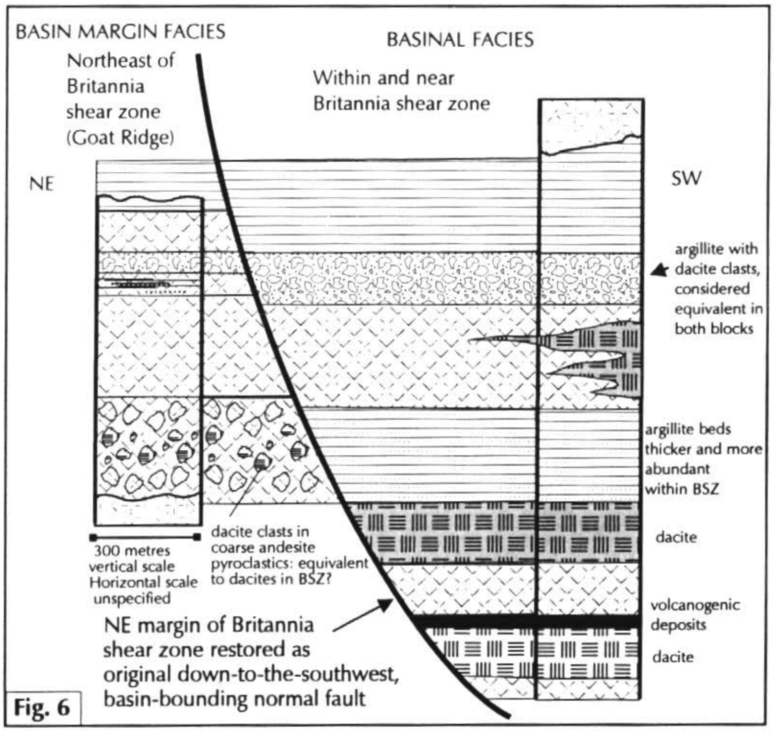


Fig. 6

Figure 5 *Local geology of the Britannia Mine (Payne* et al., *1980, with some features after Lynch, 1991).*

Figure 6 *A restoration of possible original basin geometry in the Britannia mine area using stratigraphic columns of Payne* et al., *1980. Note the increased thickness of hemipelagic sedimentary strata, and the presence of thick felsic units and sulphide mineralization, within the basin as opposed to on the horst to the northeast. For clarity, the dacite dykes that are abundant within the shear zone are not shown.*

canic) basins during thrust belt tectonics.

BASIN INVERSION: THROUGH THE LOOKING GLASS

The concept of basin inversion first came into wide use in the petroleum industry (Cooper *et al.*, 1989). An inverted basin is one that has been converted into a structural high by subsequent compression. Its bounding normal faults have been reactivated into thrusts, and its basin fill has been deformed, perhaps to a higher degree than surrounding strata. After extreme inversion, the original basin can only be recognized by the greater thickness and peculiar facies of its fill. The structural predictions of this concept provide a powerful tool in the analysis of deformed syngenetic deposits and the basins that host them.

McClay *et al.* (1989) used basin inversion to explain the complex thrust geometries around Devonian sedimentary exhalative occurrences in deep basinal strata of the northwestern Rocky Mountains. The first-order basin is known as the Kechika trough, an elongate marine basin in the western Cordilleran miogeocline that subsided from Cambrian through Early Mississippian time. The Kechika trough hosts an array of exhalative lead-zinc-barite and barite occurrences ranging from Ordovician to Devonian in age. The largest and most numerous are Late Devonian. They formed during an episode of rifting, accompanied by strong clastic influx from the western (outboard) side of the basin.

The geologists who first explored the Kechika trough in the late 1970s and early 1980s came to recognize that the sulphide deposits all lay just east of major Jura-Cretaceous thrust faults. In many cases, profound thickness and facies changes in the Devonian strata occur across these faults, suggesting that they are remobilized original sub-basin-bounding faults. This concept is given prominence in McClay *et al.* 's cross sections (Fig. 3). The regional Jura-Cretaceous thrust system imposed its northeasterly, continentward vergence on all pre-existing features. Thus the western graben-bounding normal fault has been overturned to the east to become a west-side-up thrust fault, while the eastern bounding normal fault reversed its motion to become an out-of-graben reverse fault or thrust. Within the second order basin, each sub-basin tends to form its own, independant set of thrust imbricates. Some small third-order grabens become anticlines and are squeezed out like watermelon seeds: these are called pop-up structures (Fig. 3). The resulting picture preserves a memory of the original rift basin, with its elements distorted as if in a warped mirror.

Basin inversion also helps resolve the paradox of Britannia Mine: the intimate association of classic Kuroko-type deposits with a prominent shear zone (Figs. 4-6). Argillites and felsic volcanic units of the mid-Cretaceous Gambier Group thicken markedly in the vicinity of the ore bodies; where a swarm of dacite dikes, feeders to the felsic extrusive units, parallels both the shear zone boundaries and the trend of the sulphides (Figs. 4-5; Payne *et al.*, 1980). The Britannia shear zone is a regional northwest-trending fault, part of a set of post-Gambier contractional faults in the southern Coast Mountains (Lynch, 1991; Monger, 1993). Some of them are associated with conglomerates in the Gambier Group, and show evidence of syn-Gambier normal displacement. Like the thrust faults in the Kechika trough, the Britannia shear zone may well have been a normal, basin-bounding fault, remobilized and overturned during contractional deformation (Lynch, 1991).

CONCLUSIONS

Two mental pictures clarify the structural setting of syngenetic massive sulphide deposits, whether they are sediment- or sedimentary volcanic-hosted, and whether they lie on a continent margin, ridge axis, or back-arc rift. The first emerges from scrutiny of "living" ocean floor deposits. It shows hydrothermal centres nested in grabens within grabens in the axial zones of rifts. The second is a skewed, slanted version of the first (which nevertheless obeys all the rules of section balancing!). This is the inverted basin of deformed terranes, with its positive structural morphology, reactivated bounding faults, pop-up structures, and out-of-graben thrusts.

Geologic structures, once established, have long lives and many potential episodes of remobilization. Once in its history a "break" may form part of a rift basin in which syngenetic mineralization was generated, or a channel along which the hydrothermal solutions rose. However, before and after, such a "break," as a zone of weakness, may have played vastly different roles: perhaps a basement shear zone active in the Precambrian; or later a thrust fault during arc-continent collision.

With this vision, the repeated coincidence of syngenetic deposits — and, for example, later thrust faults — becomes almost expected. For instance, on southern Vancouver Island, a string of Late Devonian volcanogenic occurrences — contemporaneous with the Buttle Lake Mine — lie along the hanging wall of the a southwest-vergent thrust fault, the Late Cretaceous Fulford Fault. At one of them, the Lara, sulphides are actually truncated by the fault. This case lends itself readily to the interpretation of basin inversion, particularly in that marked facies changes occur in the Devono-Mississippian strata across the much younger thrust fault (N. Massey, pers. comm., 1995).

If, in some virtual dimension the authors of the CIMM Special Volume could be brought together for a 50th reunion, what might their comments be on these new models? One hopes they might be pleased to note that, finally, the entire body of observations relevant to syngenetic massive sulphide deposits, structural as well as stratigraphic, had been brought to bear on the problem, and given its share of the solution.

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