Bowden, Christopher David (2007)
Epithermal systems of the Seongsan district, South Korea an investigation on the geological setting and spatial and temporal relationships between high and low sulfidation systems.
PhD thesis, James Cook University.

Chapter 1:
Introduction to the epithermal systems of the Seongsan district, South Korea

1.1 INTRODUCTION

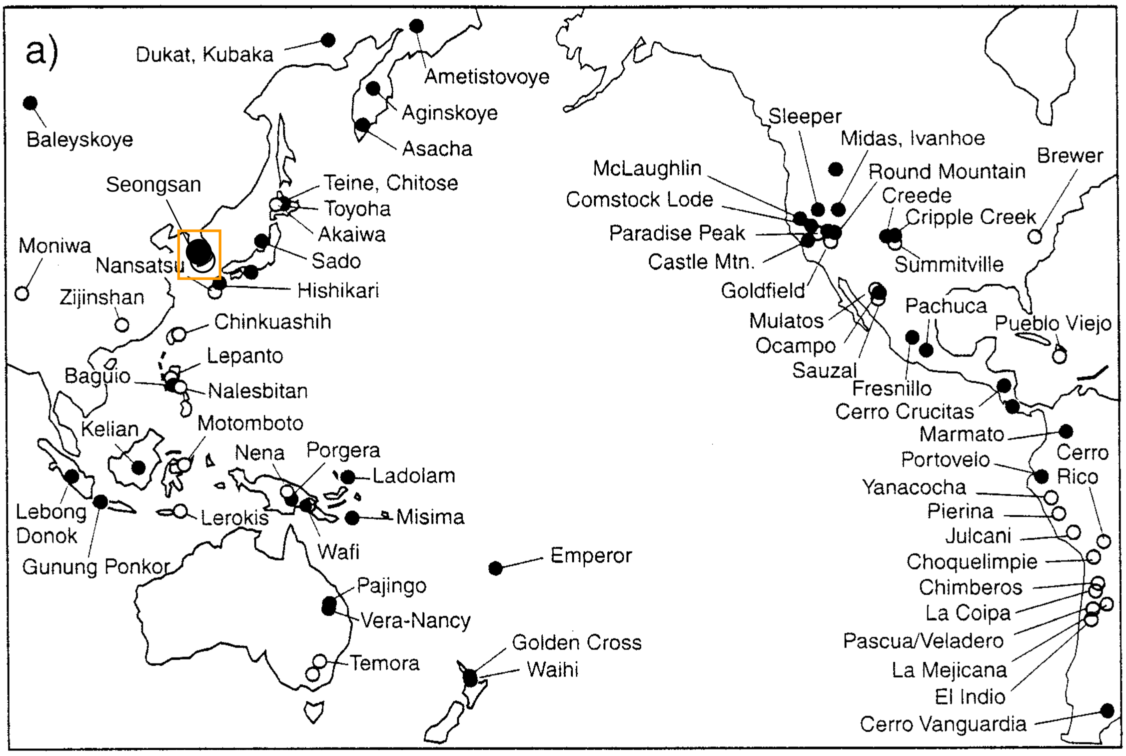
The primary objective of this project is to investigate the geological setting and the spatial and temporal relationships between the distinctly different epithermal systems in the Seongsan district of South Korea. Detailed research aims are listed in Section 1.2 after some background information on selected issues for epithermal systems is presented and discussed.

1.1.1 Epithermal Au-Ag deposits and their related hydrothermal systems

Epithermal Au-Ag deposits are an important source of precious metals, particularly within Phanerozoic orogenic belts of the circum-Pacific and southern Europe (Fig. 1-1). The large size and/or high grade of some epithermal Au-Ag deposits (Fig. 1-2) ensure that they continue to be an important exploration target. In addition to Au and Ag, epithermal deposits can also be an important source of base metals and clay-sulfate mineralisation (Kitagawa, 1999; Cooke & Simmons, 2000; Einaudi et al., 2003).

Epithermal deposits are generally hosted in subaerial volcanic rocks within both island-arc and continental-arc settings (Cooke & Simmons, 2000; Sillitoe & Hedenquist, 2003; Simmons et al., 2005), and are generally inferred to have formed at relatively shallow levels in the crust (ca. <1.5km). They generally occur within calc-alkaline andesitic-dacitic-rhyolitic arcs or bimodal (basalt-rhyolite) volcanic suites, although systems hosted in alkalic rocks are also known (Richards, 1995; Jensen & Barton, 2000). They tend to form in low differential stress or extensional tectonic settings, although examples that formed in compressive and transpressive tectonic settings are also known (Sillitoe & Hedenquist, 2003). In addition, a variety of submarine-hosted epithermal systems have also been recognised more recently (Sillitoe et al., 1996; Sillitoe & Hedenquist, 2003; Stewart, 2003; Hannington et al., 2005).

Epithermal deposits display a wide range of fluid chemistries, structural settings, alteration and ore mineral assemblages and mineralisation styles. This diversity of deposit characteristics is reflected in the numerous classification schemes that have been used in attempts to subdivide epithermal deposits (Table 1-1). The recent classification of epithermal systems, which is based on the sulfidation state of primary sulfides and results in subdivision into either high-sulfidation, intermediate-sulfidation or low-sulfidation types (Hedenquist et al., 2000; Table 1-1; Fig. 1-3), is perhaps losing popularity, with a trend back to descriptive nomenclature of individual deposits, based primarily on diagnostic hypogene gangue and alteration assemblages, but also describing ore minerals and deposit form (Cooke & Deyell, 2003; Simmons et al., 2005).



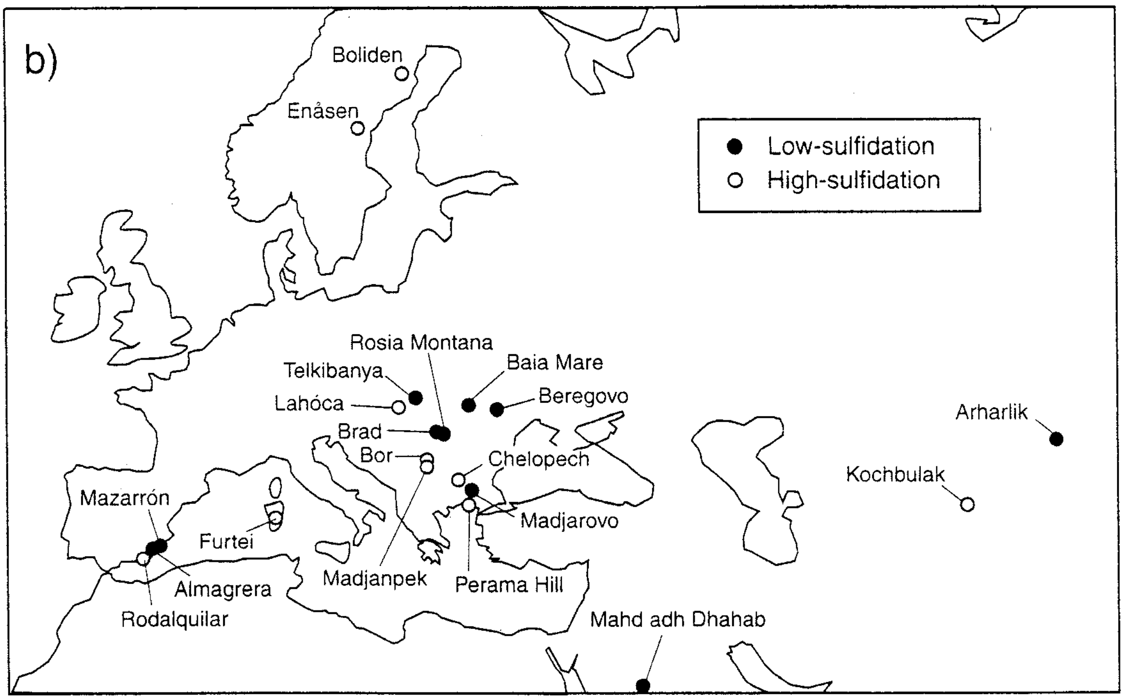


Fig. 1-1 Distribution of principal Au-Ag epithermal deposits distinguished as either high- or low-sulfidation systems from: a), the circum-Pacific region; and b), Europe. From Hedenquist et al. (2000). The box around Korea represents approximate outline of Figure 1-8A.

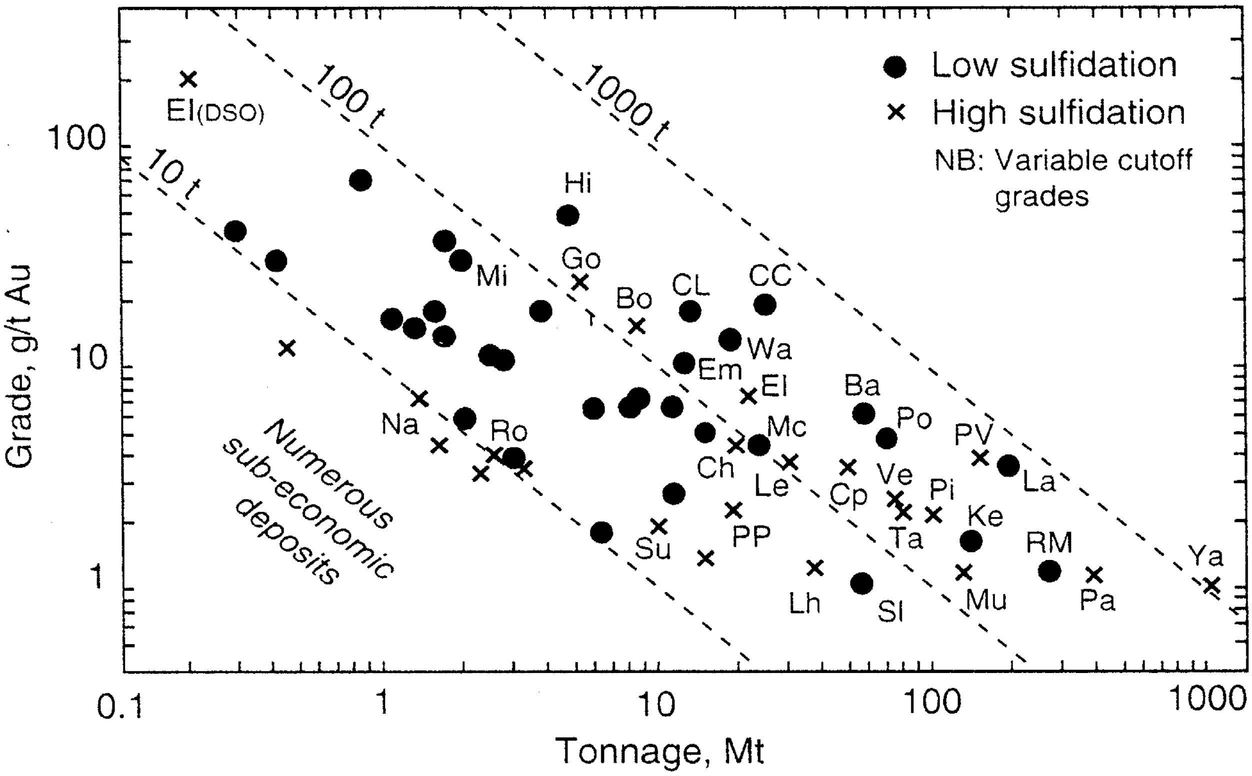


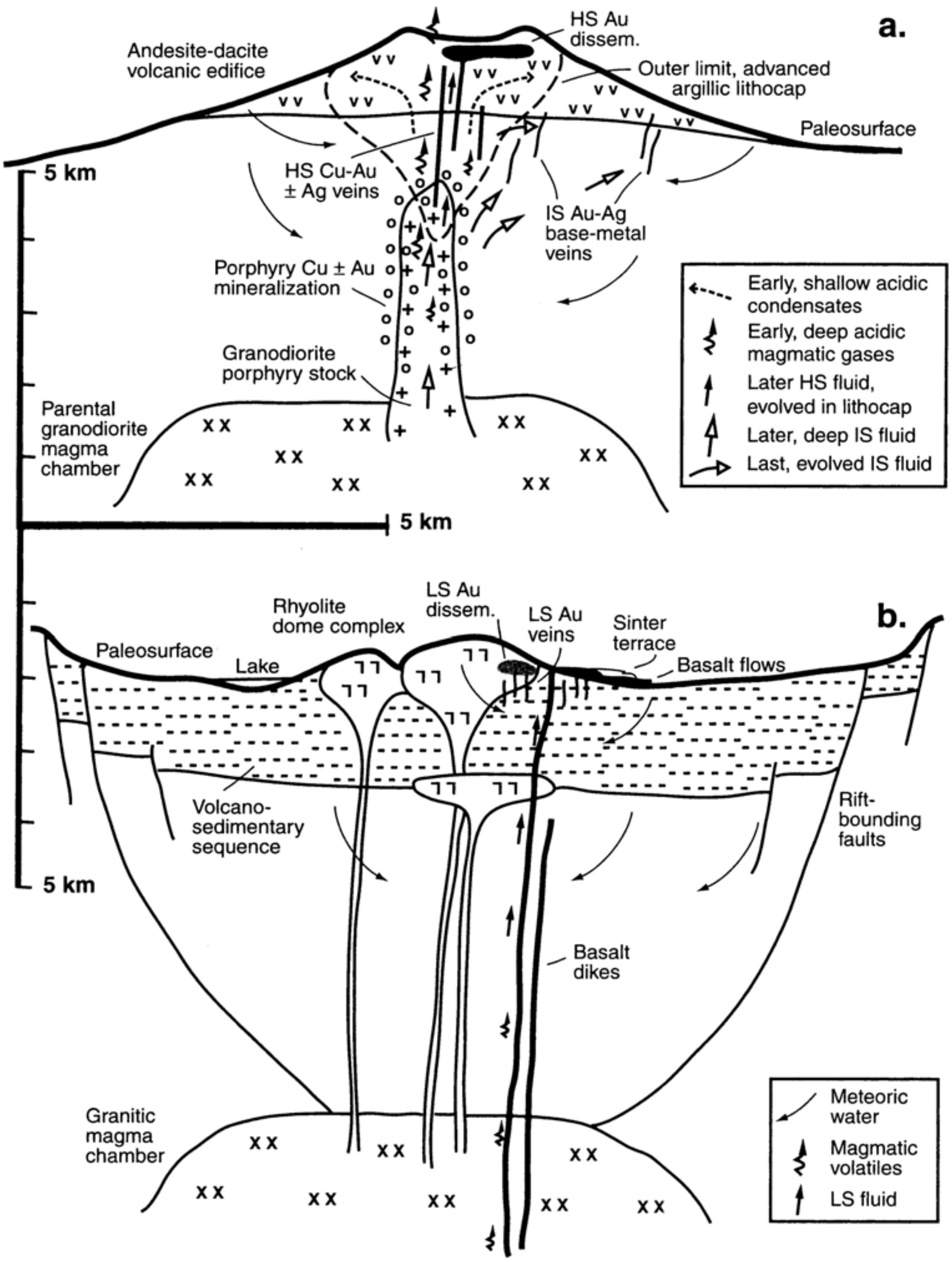
Fig. 1-2 Grade-tonnage plot showing the size of epithermal Au mineralisation from deposits classified as either high- or low-sulfidation. From Hedenquist et al. (2000).

High-Sulfidation systems: Bo=Boliden, Sweden; Ch=Chinkuashih, Taiwan; CP=Chelopech, Bulgaria; El=El Indio, Chile; El(DSO)=El Indio direct shipping ore, Chile, Go=Goldfield, Nev.; Le=Lepanto, Phil.; Mu=Mulatos, Mexico; Na=Nansatsu district, Japan; Pa=Pascua, Chile; Pi=Pierina, Peru; PP=Paradise Peak, Nev.; PV=Pueblo Viejo, DR; Ro=Rodalquilar, Spain; Su=Summitville, Col; Ta=Tambo, Chile; Ve=Veladero, Argentina; Ya=Yanacocha, Peru.

Low-Sulfidation systems: Ba=Baguio, Phil.; CC=Cripple Creek, Nev.; CL=Comstock Lode, Nev.; Em=Emperor, Fiji; Hi=Hishikari, Japan; Ke=Kelian, Indo.; La=Ladolam, PNG; Mc=McLaughlin, Cal.; Mi=Midas, Nev; Po=Porgera, PNG; RM=Round Mountain, Nev.; SL=Sleeper, Nev.; Wa=Waihi, NZ.

Table 1-1 Classification schemes for epithermal systems. Modified from Sillitoe & Hedenquist (2003).

classification scheme			references
descriptive nomenclature based on hypogene gangue and alteration minerals, ore metals, deposit form and dominant Cu-bearing minerals			Cooke & Deyell (2003), Simmons et al. (2005)
high-sulfidation	intermediate-sulfidation	low-sulfidation	Hedenquist et al. (2000), Einaudi et al. (2003) Sillitoe & Hedenquist (2003)
high-sulfidation	high sulfide+base metal, low-sulfidation	low sulfide+base metal, low-sulfidation	Sillitoe (1989, 1993)
	type 1 adularia-sericite	type 2 adularia-sericite	Albino & Margolis (1991)
alunite-kaolinite	adularia-sericite		Berger & Henley (1989)
high-sulfidation	low-sulfidation		Hedenquist (1987)
acid-sulfate	adularia-sericite		Hayba et al. (1985) Heald et al. (1987)
high-sulfur	low-sulfur		Bonham (1986, 1988)
		hot-spring type	Giles & Nelson (1982)
enargite-gold			Ashley (1982)
epithermal			Buchanan (1981)
acid	alkaline		Sillitoe (1977)
gold-alunite deposits	gold-quartz veins in andesite: argentite-gold quartz veins argentite veins base metal veins	gold-quartz veins in rhyolite gold telluride veins gold selenide veins	Lindgren (1933)
alunitic-kaolinic veins	sericitic zinc-silver veins	gold-silver-adularia veins, fluoritic tellurium-adularia gold veins	Emmons (1918)
goldfield type			Ransome (1907)



HS=high-sulfidation; **IS**=intermediate-sulfidation; **LS**=low-sulfidation.

Fig. 1-3 Proposed schematic sections of end-member volcanotectonic settings and commonly associated epithermal and related mineralisation types from Sillitoe & Hedenquist (2003). In general, high-, intermediate- and low-sulfidation epithermal systems do not occur in close proximity to each other although each is part of a broad spectrum of epithermal-type systems found in volcanic-hypabyssal settings. For an explanation of hydrothermal plumbing in epithermal systems, refer to Figure 1-6.

a. Stratovolcano within a calc-alkaline volcanic arc under a low differential stress to mildly extensional tectonic setting showing relationships between high- and intermediate-sulfidation epithermal (and porphyry) systems. This style of mineralisation would also be applicable within a dome complex.

b. Rift setting with bimodal volcanism and low-sulfidation deposits.

Note: low-sulfidation deposits can also occur within extensional arcs characterised by andesitic-dacitic-rhyolitic volcanism (i.e. setting **a.**). In addition, submarine examples of the above settings are now proving to show significant epithermal potential (Sillitoe et al., 1996; Sillitoe & Hedenquist, 2003; Stewart, 2003).

Descriptive methods address some of the limitations encountered with using sulfidation-state classification. The dominant fluid or mineral-assemblage sulfidation-state has generally been used to classify a particular deposit as either high-, intermediate- or low-sulfidation epithermal deposit. However many epithermal systems can show localised to broad-scale variations in mineral sulfidation state due to factors such as either boiling or local wall-rock influence (Einaudi et al., 2003). This classification typically does not reflect the fluid complexities, localised variations in sulfidation state or overprinting characteristics within a given system. Additionally, systems with low sulfide content are not easily classified using this system, although alteration assemblages and/or vein textures are typically used to correlate with other systems (Table 1-2).

Gangue and alteration minerals are generally present in a hydrothermal system and their mineralogy can be used to infer conditions of formation such as temperature, pressure and fluid composition. Alteration and gangue minerals can be analysed across the entire epithermal system, from peripheral alteration to core mineralisation zones throughout the paragenesis, whereas the sulfidation state of ore sulfides (if present!) only indicate the ore-fluid sulfidation state. Therefore, initial examination of epithermal systems is probably best undertaken by documenting the gangue and alteration mineral assemblages and their paragenesis (White & Hedenquist, 1995; Cooke & Deyell, 2003; Simmons et al., 2005). This will indicate the conditions of formation for the system. Then if ore sulfides are present, these can be examined to constrain the sulfidation-state of the ore-forming fluids (Hedenquist et al., 2000).

1.1.1.1 Comparison of sulfidation-state with descriptive models for epithermal systems

Ore mineral assemblages in high-sulfidation systems, by definition, include sulfides of high sulfidation state, such as enargite, luzonite, covellite-digenite, famatinite and orpiment (Table 1-2). Alteration assemblages that commonly form in association with the development of high-sulfidation mineralisation include alunite, quartz, pyrophyllite, kaolinite and rarely diaspore, andalusite, and zunyite. These high-sulfidation systems are analogous to acid-sulfate systems (Table 1-1). High-sulfidation systems form from oxidised, hot, strongly acidic fluids that include a significant to dominant magmatic component. Economically significant Au and Ag are generally hosted in late veins that cut the earlier alteration with only minor sub ppm Au directly associated with the main alteration stage/s (Fig. 1-4; Table 1-2).

Ore mineral assemblages in low-sulfidation systems, by definition, include sulfides of low sulfidation state, such as arsenopyrite±pyrrhotite, sphalerite, galena, tetrahedrite-tennantite and chalcopyrite (Table 1-2). Alteration assemblages that commonly form in association with the development of low-sulfidation mineralisation include adularia, sericite, chlorite, mixed layer clay and siliceous alteration. These low-sulfidation systems are analogous to adularia-sericite systems (Table 1-1). Low-sulfidation systems form from near neutral, reduced, low-temperature fluids of largely meteoric origin. Au and Ag are hosted in either narrow bonanza-grade quartz vein lodes, stockworks of quartz veinlets and/or more rarely disseminated through broader volumes of altered permeable country rock (Fig. 1-5; Table 1-2).

Intermediate-sulfidation deposits by their nature can show a broad variety of characteristics that are common to both high- and low-sulfidation deposits. Intermediate-sulfidation deposits overlap both high- and low-sulfidation alteration and mineral assemblages, but intermediate-sulfidation deposits generally do not contain the very high pH stable minerals such as adularia or pyrrhotite, or very low pH stable minerals such as alunite or enargite (Table 1-2). Intermediate-sulfidation fluids are thought to form from either mixing of high- and low-sulfidation fluids, or from a cooling high-sulfidation fluid (Einaudi et al., 2003).

The current understanding of hydrothermal plumbing for epithermal systems and the relationship between them is schematically represented in Figure 1-6. The variety of sulfide assemblages in epithermal deposits that reflect sulfidation state, from very low and low through intermediate to high and very high, are represented in Figure 1-7.

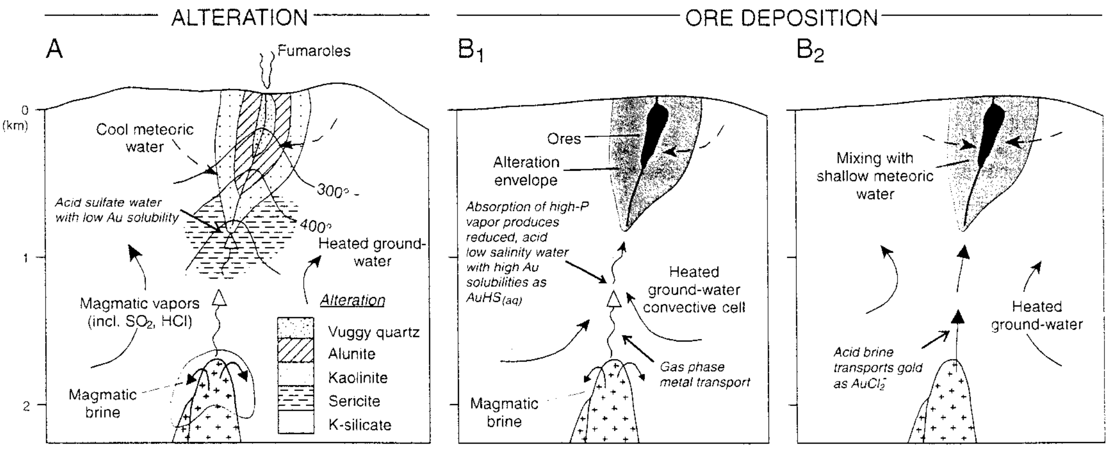


Fig. 1-4 A schematic two-stage model for alteration and ore deposition in high-sulfidation hydrothermal systems after Cooke & Simmons (2000), modified from Arribas Jr (1995). **Alteration Stage A** is the ground preparation stage, whereby magmatic gases generate an acid sulfate high-sulfidation hydrothermal fluid that is responsible for the initial stage of residual silica alteration and surrounding more extensive advanced argillic alteration (typically barren with respect to Au and Ag). **Ore Deposition** is thought to involve either of two possible scenarios, **Stage B_1** involves gold deposition from acid chloride low-sulfidation waters, or **Stage B_2** involves gold deposition from acid chloride brines.

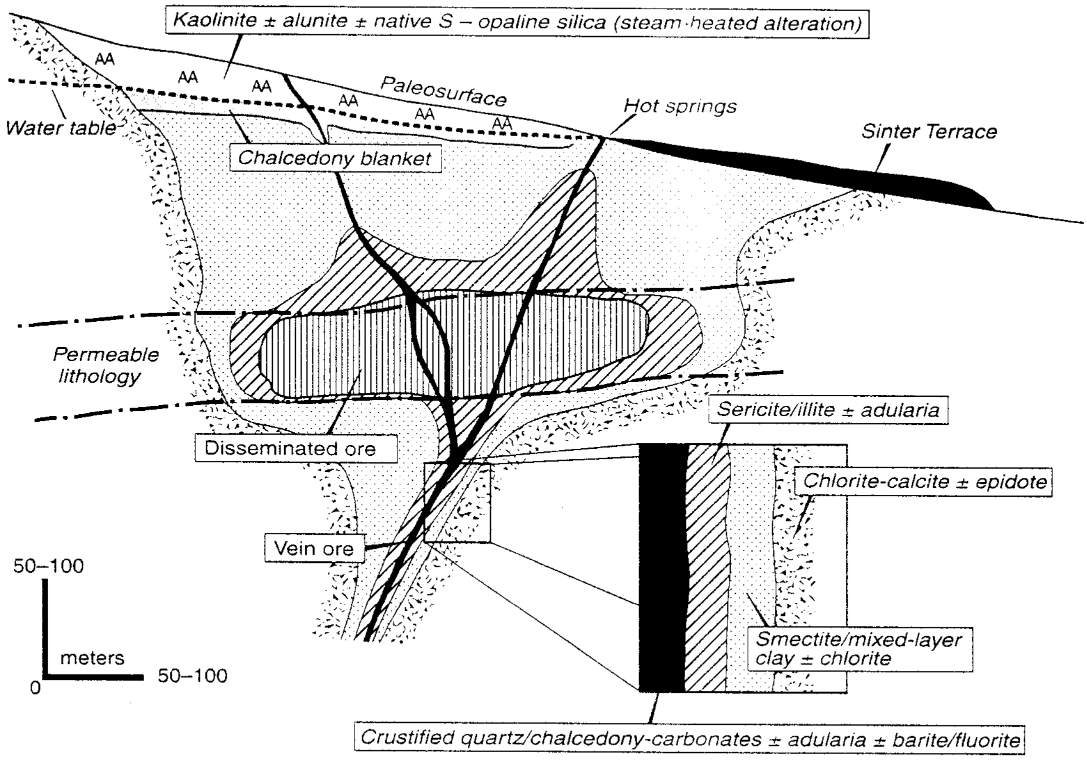


Fig. 1-5 Schematic model of low-sulfidation alteration and mineralisation, from Hedenquist et al. (2000), modified from Buchanan (1981). Fluid flow is typically focussed through structures. Alteration haloes generally develop around the primary fluid zones, which are typically coincident with the vein systems, in contrast to the more pervasive and extensive high-sulfidation system alteration haloes.

Table 1-2 Principle field-oriented characteristics of epithermal deposit types. From Sillitoe & Hedenquist (2003).

	High-sulfidation		Intermediate-sulfidation	Low-sulfidation	
	oxidised magma	reduced magma[1]		subalkaline magma	alkaline magma
type example	El Indio, Chile (vein); Yanacocha, Peru (disseminated)	Potosi, Bolivia	Baguio, Philippines (Au-rich); Fresnillo, Mexico (Ag-rich)	Midas, Nevada	Emperor, Fiji
genetically related volcanic rocks	mainly andesite to rhyodacite	rhyodacite	principally andesite to rhyodacite but locally rhyolite	basalt to rhyolite	alkali basalt to trachyte
key proximal alteration minerals	quartz-alunite/ APS[2]; quartz-pyrophyllite/ dickite at depth	quartz-alunite/APS; quartz-dickite at depth	sericite; adularia generally uncommon	illite/smectite-adularia	roscoelite-illite-adularia
silica gangue	massive fine-grained silicification and vuggy residual quartz		vein-filling crustiform and comb quartz	vein-filling crustiform and colloform chalcedony and quartz;	
				carbonate replacement textures	quartz deficiency common in early stages
carbonate gangue	absent	absent	common, typically including manganiferous varieties	present but typically minor and late	abundant but not manganiferous
other gangue	barite common, typically late		barite and manganiferous silicates present locally	barite uncommon; fluorite present locally	barite, celestite, and/or fluorite common locally
sulfide abundance	10-90 vol %	10-90 vol %	5-20 vol %	typically <1-2 vol % (but up to 20 vol % where hosted by basalt)	2-10 vol %
key sulfide species	enargite, luzonite, famatinite, covellite	acanthite, stibnite	sphalerite, galena, tetrahedrite-tennantite, chalcopyrite	minor to very minor arsenopyrite ± pyrrhotite; minor sphalerite, galena, tetrahedrite-tennantite, chalcopyrite	
main metals	Au-Ag, Cu, As-Sb	Ag, Sb, Sn	Ag-Au, Zn, Pb, Cu	Au ± Ag	Au ± Ag
minor metals	Zn, Pb, Bi, W, Mo, Sn, Hg	Bi, W	Mo, As, Sb	Zn, Pb, Cu, Mo, As, Sb, Hg	
Te and Se species	tellurides common; selenides present locally	none known but few data	tellurides common locally; selenides uncommon	selenides common; tellurides present locally	tellurides abundant; selenides uncommon

1 – The Potosi deposit has a lack of primary sulfides and as such has been classified under a variety of sulfidation states. The presence of high-sulfidation style alteration assemblages however should clarify its position as a high-sulfidation deposit.

2 – APS represents aluminium-phosphate-sulfate minerals.

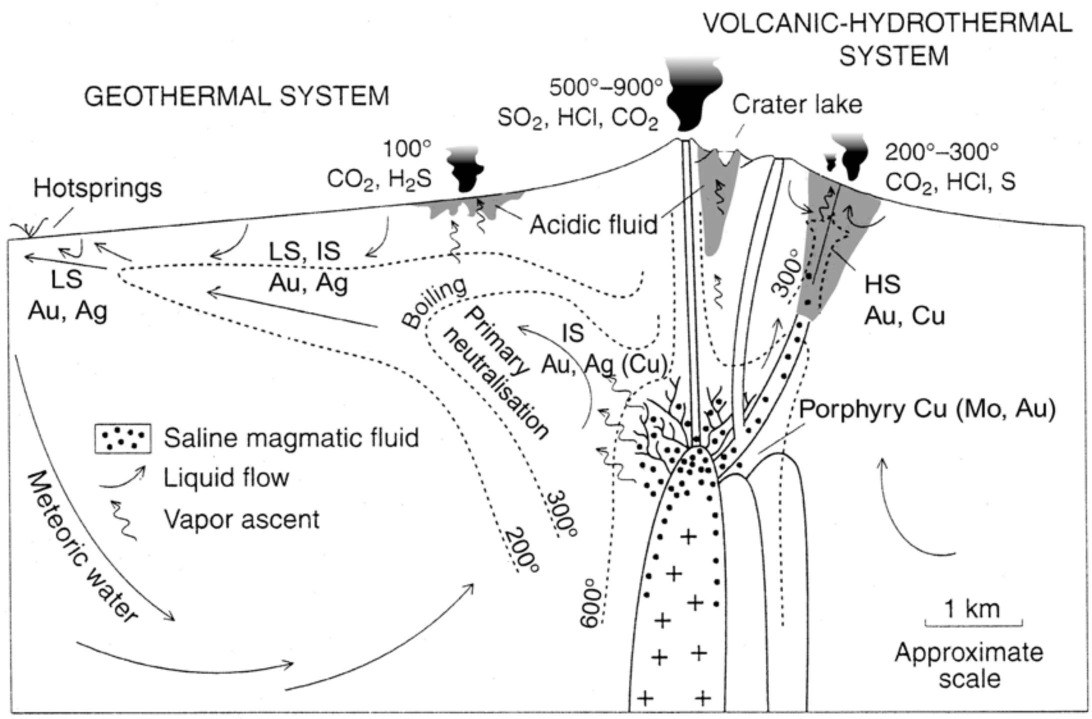


Fig. 1-6 Illustration of the generalised hydrothermal plumbing and settings of epithermal systems relative to plutonic activity within a calc-alkaline stratovolcano volcanic arc setting with a low differential stress to mildly extensional tectonic setting. Modified from Hedenquist et al. (2000); fluid data from Cooke & Simmons (2000). Although these systems share a common hydrothermal and tectonic setting, this spatial representation of all epithermal systems occurring together is not commonly observed.

HS: High-sulfidation systems are generally fluid-buffered systems dominated by hot, magmatic, oxidised, acidic fluids, which are inferred to have a direct link to underlying hypabyssal plutonic activity. At surface, these fluids form acid-sulfate waters or acid-chloride-sulfate waters. **LS: Low-sulfidation** systems are generally rock-buffered systems dominated by lower temperature, meteoric, near-neutral pH, reduced fluids. At surface, these fluids can form chloride water hot springs derived from interactions between deeply circulating meteoric water and minor magmatic components (e.g.: H_2O, CO_2, SO_2, H_2S, HCl). These chloride waters are thought to represent the most important low-sulfidation water for aqueous transport of precious metals. Other waters that can form in low-sulfidation systems are CO_2-rich steam-heated water and acid-sulfate steam-heated waters. CO_2-rich steam-heated waters are known to form from modern-day equivalents such as the Broadlands-Ohaaki geothermal system (Simmons & Browne, 2000). Acid-sulfate steam-heated waters form from the oxidation of H_2S in the vadose zone. **IS: Intermediate-sulfidation** systems as the name suggests represents a mix of high- and low-sulfidation states and hence a mix of characteristics. Generally, although not exclusively, intermediate-sulfidation systems show a stronger genetic affinity to high-sulfidation systems.

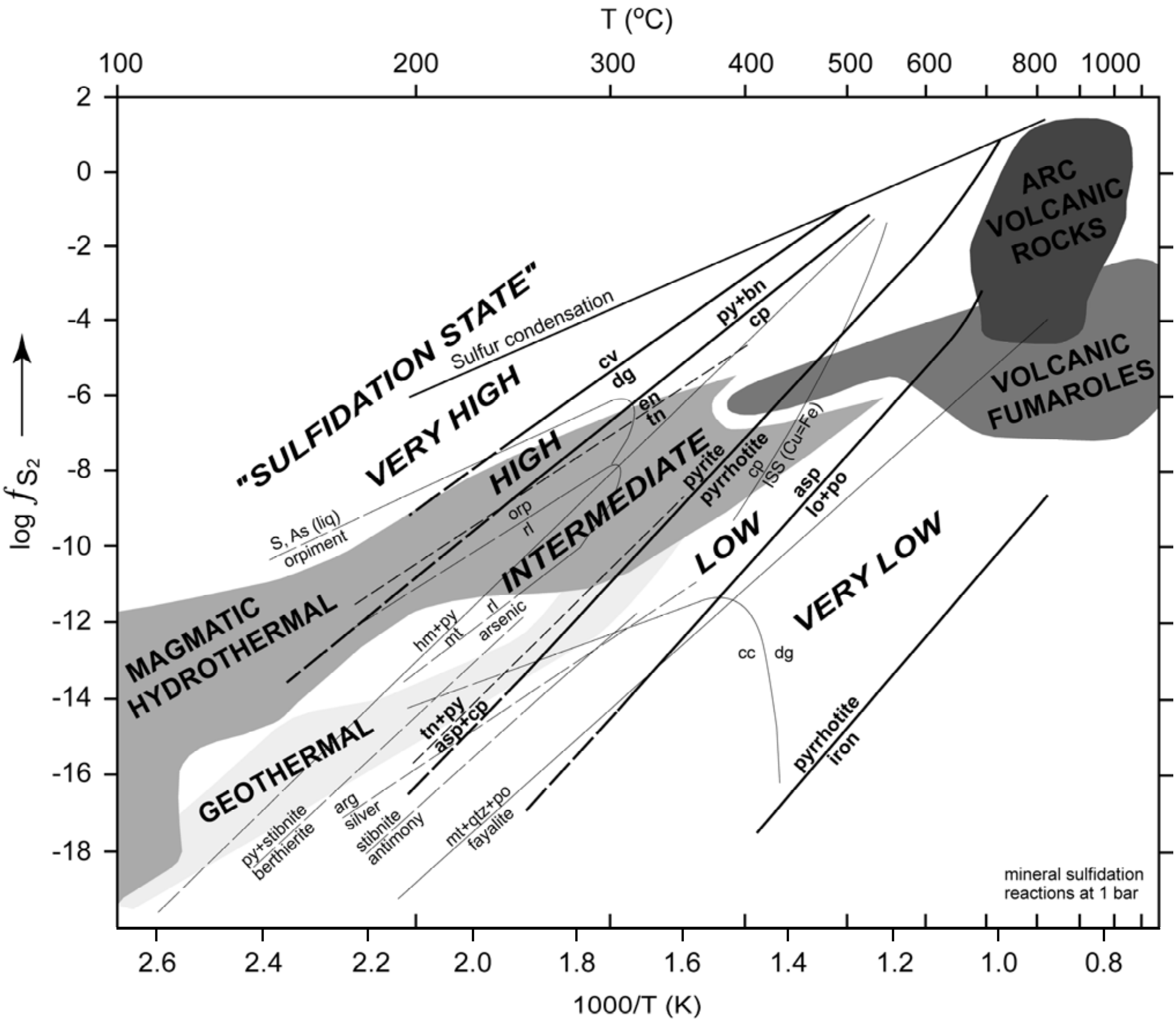


Fig. 1-7 A log fS_2 vs. temperature diagram showing mineral sulfidation reactions at 1 bar. Sulfidation reactions used to define sulfidation state are in bold. Shaded areas represent sulfidation fields for arc volcanic rocks and active hydrothermal systems. From Einaudi et al. (2003); for details of reactions, calculations and sources of original data see Einaudi et al. (2003; Fig. 4). Mineral abbreviations this figure: arg = argentite; asp = arsenopyrite; bn = bornite; cc = chalcocite; cp = chalcopyrite; cv = covellite; dg = digenite; en = enargite; hm = hematite; lo = lollingtonite; mt = magnetite; orp = orpiment; po = pyrrhotite; py = pyrite; qtz = quartz; rl = realgar; tn = tennantite

1.1.2 Epithermal systems of the Seongsan district: research themes

The Chollanam Province in southwest Korea (ca. 12,000km^2; Fig. 1-8A, B), and in particular, the Seongsan district (ca. 20km^2; Figs. 1-8C & 1-9), host numerous and extensive clay-sulfate-silica deposits. Based on the extensive kaolinite-dickite and alunite alteration, previous workers have correlated these clay-sulfate-silica deposits with high-sulfidation systems elsewhere (Kim, 1992a; Yoon, 1993, 1995). Associated zones of advanced argillic alteration have been described by Kim et al. (1990); Moon et al. (1990); Kim (1991, 1992b, a); Kim et al. (1992); Kim & Nagao (1992); Kim & Kusakabe (1993); Yoon (1993, 1995); Koh (1996); Koh & Chang (1997); and, Koh et al. (2000). Some are exploited as commercial sources of kaolinite and dickite. Alunite has also been mined locally where sulfidation of the host rocks is particularly intense. Kim (1992a) and Yoon (1993, 1995) confirmed the presence of sub-economic Au grades in material extracted from the clay-sulfate mines at Seongsan, and recognised the overall high-sulfidation epithermal nature of the related hydrothermal systems.

The Seongsan district also hosts several styles of Au-Ag mineralised epithermal systems that have only been recognised recently, which are inferred to represent low-sulfidation systems (Forbes, 1999; Kirwin & Forbes, 1999; Kirwin et al., 1999; Panther et al., 2000; Choi et al., 2005). Little is known about their geological setting, any structural controls on their location, or their relationship, if any, to the nearby clay-sulfate-silica deposits (Fig. 1-8). Styles of mineralisation include bonanza epithermal vein-style Au-Ag mineralisation at the Eunsan mine, vein-hosted Au-Ag (±base metal) mineralisation within flow dome and intrusive complexes at the Moisan prospect and replacement style Au-Ag mineralisation at the Chunsan prospect.

The occurrence of high- and low-sulfidation epithermal systems in close proximity to each other is not common, despite them apparently sharing similar tectonic settings. It is not known whether the various epithermal systems in the Seongsan district are related parts of a single metallogenic event, or are different events with consistent crosscutting field relationships and different fluid and metal sources.

The close proximity of unmetamorphosed and relatively undeformed high- and low-sulfidation systems within the Seongsan district provides an opportunity to further analyse relationships between these distinct styles of epithermal hydrothermal activity. In addition, the presence of both low- and high-sulfidation systems in the Seongsan district provide an opportunity to test postulated relationships between high-, intermediate- and low-sulfidation systems, as proposed by Hedenquist et al. (2000).

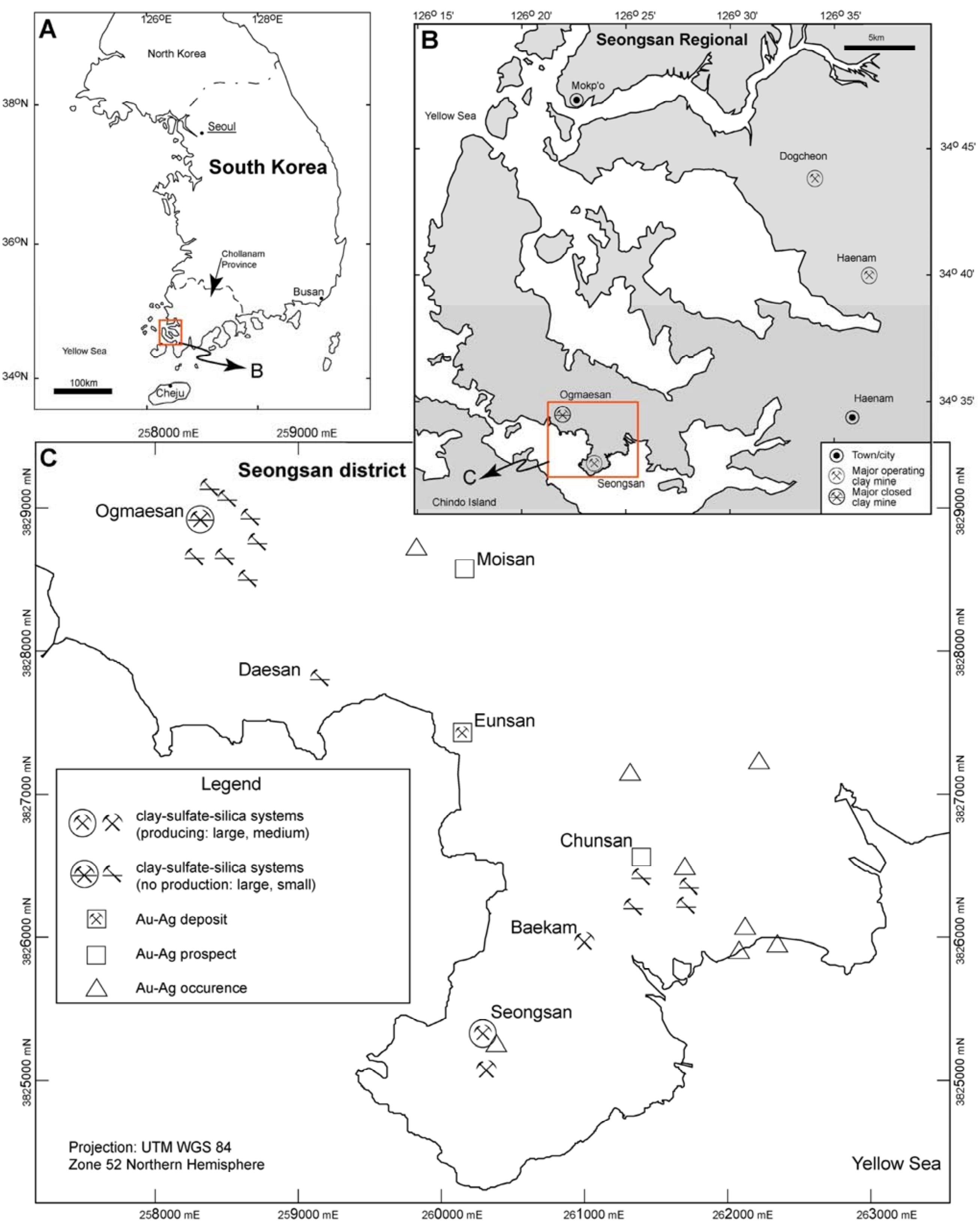


Fig. 1-8 Location of the Seongsan district within the Chollanam Province, South Korea. **A**: Korean peninsula with location of the Chollanam Province, **B**: Seongsan region with major clay-sulfate deposits inferred to be correlatives of high-sulfidation systems and **C**: Seongsan district with the location of epithermal systems recognised to date.

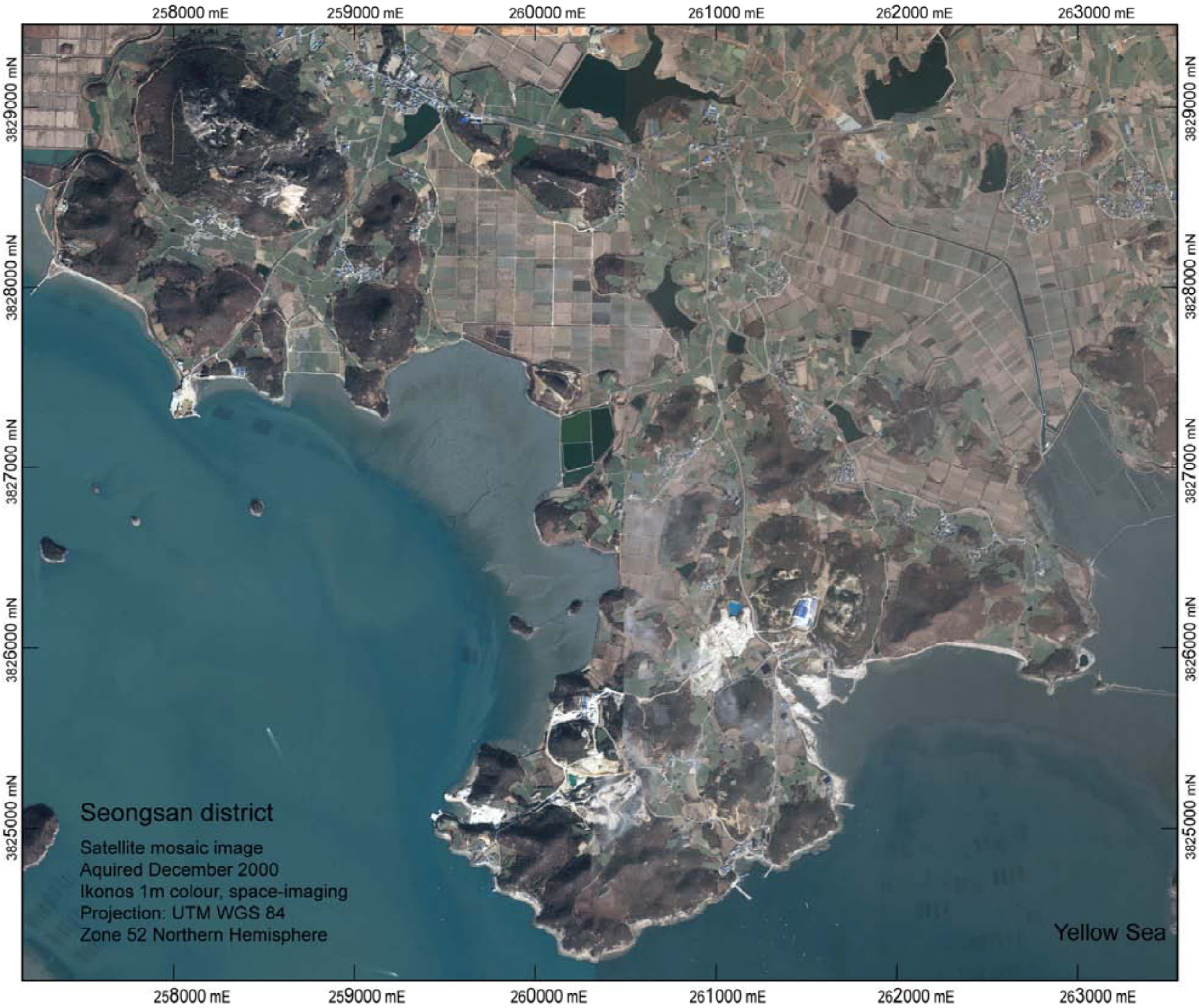


Fig. 1-9 Satellite mosaic image of the Seongsan district. This figure highlights to some extent the amount of farming and patchy outcrop of the district. This image has been produced to underlay Figure 1-8C.

Extensive exploration in the Seongsan district indicates that the clay-sulfate-silica systems contain only sub-economic amounts of Au. Koh & Chang (1997) analysed 527 altered drill core samples for Au (intervals unknown) obtained from clay exploration programs. They defined that the surface projection of greater than 1ppm Au covered an area of 0.3km^2 out of an area of alteration that is in the order of 10km^2. Vertically, the mineralised zones occur between 11mRL and -160mRL. Based on re-sampling of the Seongsan Clay Mining Co. diamond drill core by Ivanhoe Mines Ltd. geologists (Panther et al., 2000), continuous intervals of greater than 1ppm Au were typically no greater than 20m in vertical continuity. The amount of Au mineralisation is equivalent to approximately 55,000oz of Au assuming homogeneous and continuous Au distribution for 20m of vertical extent covering a 0.3km^2 area. These assumptions would be a gross overestimate of Au oz based on additional current data now available. This is in marked contrast with some systems, such as the Pueblo Viejo district, which hosts numerous deposits for a combined total of 40 million oz of Au, 240 million oz Ag, 3 million tonnes of Zn, and 0.4 million tonnes of Cu (Nelson, 2000).

Analysis of mineralised high-sulfidation systems indicates a complex paragenesis in which Au (±Cu) deposition occurs after extreme acid high-sulfidation leaching. These late fluids responsible for high-grade Au development are typically intermediate- to low-sulfidation fluids (Arribas Jr, 1995; Cooke & Simmons, 2000; Hedenquist et al., 2000; Einaudi et al., 2003; Sillitoe & Hedenquist, 2003). Implication of current literature then is that a Au-rich high-sulfidation system generally requires a separate, typically intermediate- to low-sulfidation fluid phase after high-sulfidation alteration to make an orebody. However there is relatively little information in the literature that describes barren high-sulfidation systems, or possible discriminators between economic and sub-economic systems. Barren to very weakly mineralised high-sulfidation systems in the Seongsan district offer an opportunity to further investigate this.

The Seongsan high-sulfidation deposits may lack economically significant Au but clearly contain substantial clay-sulfate of commercial quality suitable for economic extraction. High-sulfidation systems elsewhere therefore have the potential to provide economic resources of commodities other than Au. The Seongsan clay-sulfate-silica deposits offer an opportunity to identify those features that result in development of large amounts of commercial quality kaolinite, dickite and alunite as opposed to just Au.

1.2 PRIMARY OBJECTIVE AND DETAILED AIMS OF THIS RESEARCH

The primary objective of this project is to investigate the geological setting and the spatial and temporal relationships between the distinctly different epithermal systems in the Seongsan district. This thesis comprises six chapters that focus on the following aims:

1. Investigate and document the local geology of the Seongsan district focussing on field relationships and the general geological setting of the epithermal deposits and prospects **(Chapter 2)**.

2. Document the mineral assemblages and geological setting for the epithermal deposits and prospects in the district, primarily focussing on the geological and structural controls on the location of mineralisation and alteration and determining the paragenetic sequences of geological and hydrothermal events **(Chapter 3**).

3. Classify the epithermal systems of the Seongsan district, based on the geological frameworks proposed by Hedenquist et al. (2000) and Cooke & Deyell (2003), and evaluate each as a valid classification system for epithermal systems **(Chapter 3)**.

4. Date the low-sulfidation epithermal systems of the Seongsan district using the step-wise $^{40}Ar/^{39}Ar$ method to provide absolute constrains on the age of these systems to compare with published ages of the nearby high-sulfidation systems **(Chapter 4)**.

5. Conduct fluid inclusion and oxygen, hydrogen and sulfur isotope studies of selected vein and mineral assemblages in order to constrain a fluid genesis for each distinctly different epithermal system and gain an insight into their conditions of formation **(Chapter 5)**.

6. Test postulated relationships between high-, intermediate- and low-sulfidation systems as proposed by Hedenquist et al. (2000) by comparing and contrasting various epithermal systems within the Seongsan district and known systems elsewhere **(Chapter 6)**.

7. Investigate possible ore controls on clay-alunite versus Au-Cu mineralised high-sulfidation systems by comparing and contrasting the clay-alunite deposits of the Seongsan district with known Au-Cu mineralised high-sulfidation systems elsewhere **(Chapter 6)**.

8. Synthesise data and develop an exploration philosophy for Au-Ag and clay/sulfate epithermal deposits in South Korea and similar adjacent terranes **(Chapter 6)**.

A variety of information was gathered during investigation of the above topics. Initially surface geological mapping and sampling was conducted over 20km^2 at a scale of 1:5,000. Outcrop extent varies from sparse exposures in the cultivated flat-lying areas to full exposure in the mine workings that average less than 10 percent of the whole Seongsan district. Geological contacts were walked out in the field in order to maintain a high level of control on mapping. Logging of diamond drill holes, open pit and underground mine exposures was undertaken to supplement the mapping and gain a clearer three-dimensional understanding of the geology. Structure contour analysis was used to clarify the relationship of geological contacts and faults seen in outcrop and core. Hand sample description and thin section work was carried out on all significant rock types to help constrain their depositional environment. Appendix 1 lists all samples referenced within this thesis, now stored at James Cook University.

The primary focus whilst field mapping and core logging was to identify the host rocks, to characterise any dominant structural features and to determine the extent and type of any alteration or mineralisation that may be present. This work was the first detailed systematic geological investigation undertaken of the Seongsan district, and has been compiled as a 1:5,000 scale geological map and cross sections that illustrate many of the geological relationships in the Seongsan district. Detailed 1:500 scale maps and cross sections of the prospects and deposits were also compiled.

A combination of petrographic studies, XRD, electron microprobe, bulk rock assays, fluid inclusion and stable isotope analyses were undertaken on each of the epithermal systems to further elucidate the mineral assemblages, paragenesis, fluid chemistry, P-T conditions of alteration development, and fluid and metal sources. In addition $^{40}Ar/^{39}Ar$ dating of samples from the recently discovered Au-Ag mineralised deposits and prospects inferred to represent low-sulfidation style epithermal systems was undertaken to determine whether they formed at approximately (±2Ma) the same time as the adjacent clay-sulfate-silica deposits or formed at distinctly different times.

This data was used to clarify a number of issues, including: the relationships between the various epithermal systems observed within the Seongsan district; characteristics that distinguish Au-poor and Au-rich high-sulfidation systems; and features favourable for the development of clay-sulfate versus Au deposits in high-sulfidation settings. In addition, the information gathered during this project was analysed in conjunction with regional geological data to develop an exploration model for epithermal Au-Ag / clay-sulfate deposits that could be utilised in similar terranes that occur throughout southern Korea, southeastern China, southwestern Japan and far eastern Russia.

1.3 GENERAL GEOLOGY OF THE SEONGSAN DISTRICT

1.3.1 Orogenies, tectonics and regional geology

1.3.1.1 Basement Precambrian metamorphic complex

Basement Precambrian rocks in the Seongsan district consist of banded gneiss, migmatite gneiss and mica schist (Kim, 1991; Koh, 1996). These rocks belong to the Okchon Fold Belt, which has been affected by low- to medium-grade metamorphism. The detailed stratigraphy and age of the Okchon Group is unclear, but deposition is thought to have initiated during intraplate rifting before the Late Proterozoic (Chough et al., 2000). The Okchon Fold Belt forms a 50 to 100km wide northeast-trending belt, which is bounded by regional scale sinistral strike-slip faults that separate it from the Kyonggi massif to the north from and the Yongnam massif to the south (Fig. 1-11).

1.3.1.2 Tectonics of the area prior to the Late Cretaceous (ca. 80Ma)

Major orogenic and tectonic events in Korea occurred during the Late Paleozoic and Mesozoic eras (Chough et al., 2000). In the Precambrian, the Kyonggi massif, the Okchon Fold Belt and the Yongnam massif were adrift from China. During the *Songrim Orogeny* (Late Permian to Early Triassic), these blocks collided and accreted to what is now North Korea. By Early to Late Jurassic, the *Daebo Orogeny* was producing dextral shearing, associated thrusting, and folding in a transpressional tectonic regime. The *Daebo Orogeny* was initiated by orthogonal northwestward subduction of the Izanagi Plate under the Asian continent (Chough et al., 2000; Fig. 1-10 A). By Early Cretaceous, the convergence vector of the Izanagi Plate had rotated to an oblique northward direction (Fig. 1-10 B), resulting in large-scale sinistral strike-slip faulting, and the subsequent development of pull-apart basins in a transtensional tectonic regime within which Cretaceous sedimentary sequences were deposited (Fig. 1-11, Fig. 1-12; Chough et al., 2000). At around 85Ma, the Izanagi Plate had migrated northward and the Kula Plate was being subducted under East Asia in a transpressional tectonic regime (Fig. 1-10 C).

1.3.1.3 Mesozoic igneous activity prior to the Late Cretaceous (ca. 80Ma)

Granitoid plutonism is associated with both the Songrim and Daebo Orogenies. Triassic plutons are commonly foliated while Jurassic plutons tend to be massive and relatively undeformed (Kim, 1991; Koh, 1996). Precambrian rocks of the Seongsan district were intruded by the Mesozoic Daebo Series granitoids during the *Daebo Orogeny* (Section 1.3.2.1). Sani granite (144.8±1.9Ma, $^{40}K/^{40}Ar$, Kim & Nagao, 1992) is exposed on the Sani peninsula 8km north of the Seongsan field area where it forms basement to the overlying volcanic and sedimentary rocks which host the Seongsan district epithermal systems. The Sani granite is composed mainly of coarse-grained biotite granite and less commonly of medium- to coarse-

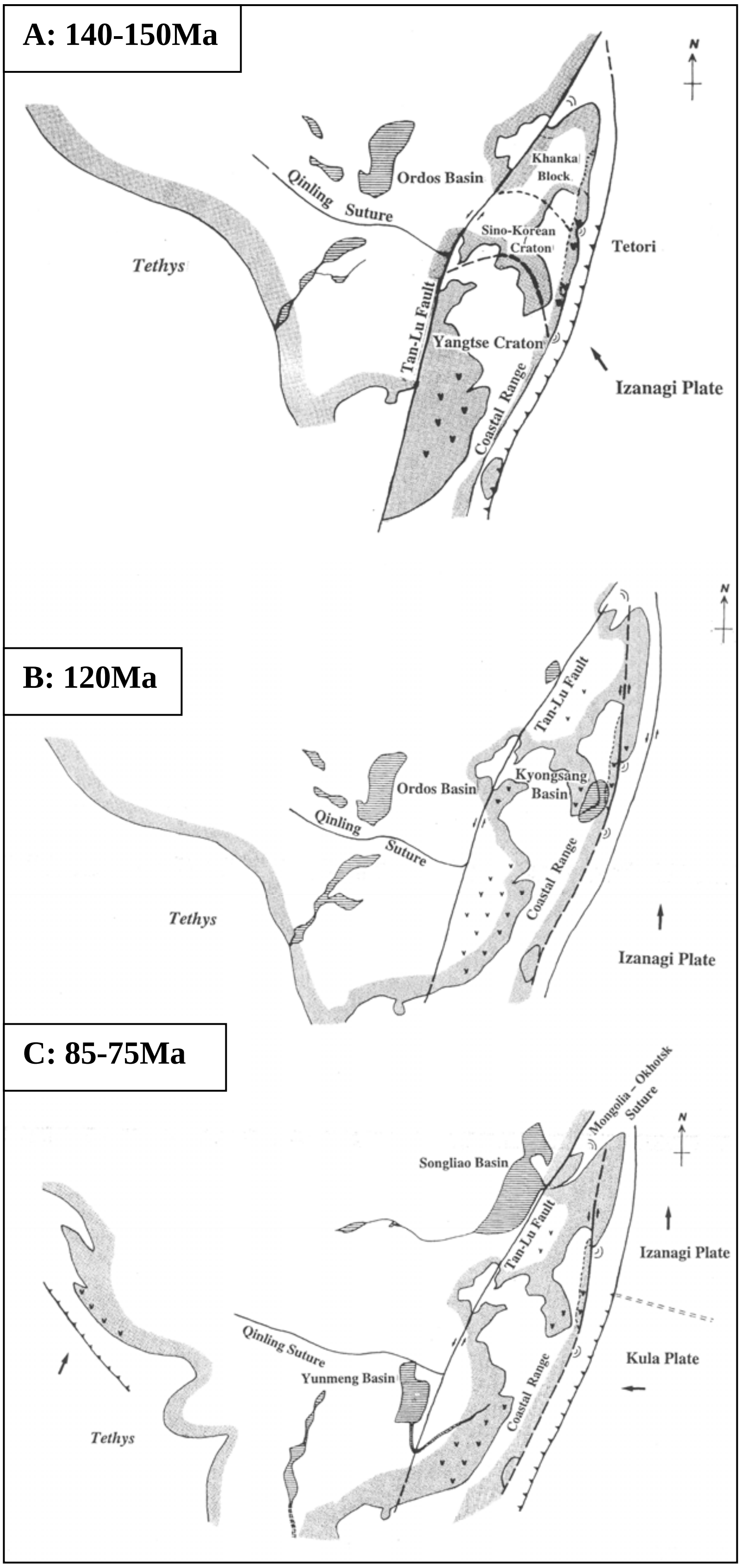


Fig. 1-10 Tectonic development of East Asia from Late Jurassic to Late Cretaceous. Shaded parts indicate ancient and modern sea-coasts; ‘v’ pattern indicates igneous activity.

Note the Cretaceous volcanic rocks extend from southeast China, through Korea into southwest Japan and continue into parts of Russia. Ages of magmatism are oldest in southeast China and young to the northeast, coincident with northward movement of the Izanagi Plate. At ca. 120Ma, igneous activity in Korea was related to plume activity and not from magmatism associated with subducting plates. Subsequently at ca. 85 to75Ma, the subduction of the Kula plate re-initiated plate-convergence-driven magmatism in the area. See text for other detail. Figure after Okada (2000).

grained hornblende-biotite granite (Koh, 1996). The Daebo series granites are more common in the central to northern parts of South Korea (Section 1.3.2) and were typically emplaced at depths of >5km (Tsusue et al., 1981). Late Jurassic to Early Cretaceous magmatism is thought to be due to plume activity (Okada, 2000); i.e. the Kyongsang basin in South Korea which hosts the Seongsan district, hatched area in Fig. 1-10 B).

1.3.1.4 Cretaceous Yuchon Group sediments, intrusive and volcanic rocks

Cretaceous volcanic rocks of the Yuchon Group unconformably overlie the Daebo Series granites and Precambrian metamorphic rocks (Kim, 1991; Koh, 1996). The Yuchon Group includes Cretaceous sedimentary rocks, sub-volcanic intrusions and related acid volcanic rocks. The Yuchon Group is divided into the conformable Hwawon, Uhangri and Haenam Formations (Koh, 1996). Rocks exposed at surface in the Seongsan district belong to the Hwangsan Tuff of the Haenam Formation. The regional geology of the Seongsan area is shown in Figure 1-13.

The Hwawon Formation is composed of interlayered andesitic lapilli and crystal-lithic tuff, fine-grained trachyandesite, basalt and andesite lava, and red-brown siltstone. Drilling data derived during testing of the overlying Uhangri Formation for oil-bearing shales and field relationships suggest that the Hwawon Formation forms discontinuous lenses rather than an extensive continuous unit within the Seongsan district compared with its more widespread regional extent (pers. comm. Reedman, Nov. 2003). $^{40}K/^{40}Ar$ age dating of basalt within the Hwawon Formation indicates an age of 103.4±2.5Ma (Kim & Nagao, 1992).

The Uhangri Formation comprises ca. 250-450m of black shale, laminated siltstone and mudstone, tuffaceous sandstone, chert and calcareous siltstone with minor intercalated volcanogenic units (Kim, 1991; Koh, 1996) deposited in a lacustrine setting. Locally, this unit hosts numerous footprints and trackways of dinosaurs, pterosaurs, birds and arthropods (Hwang et al., 2002), and plant fossils (Chun & Chough, 1995). $^{40}K/^{40}Ar$ age dating of andesite within the Uhangri Formation indicates an age of 95.4±2.9Ma (sample referred to as Inji andesite within the Uhangri Formation; Kim & Nagao, 1992).

The Haenam Formation includes four dacitic to rhyolitic tuff members denoted from oldest to youngest as the Hwangsan, Haenam, Seoho and Yongdang members (Koh, 1996). Unconformably overlying these is an altered volcaniclastic debris flow breccia, herein referred to as AVdb, which has been referred to by previous workers by many different names including ‘acidic tuff’, ‘acidic lava’, ‘Seongsan-Bukok tephra’ and ‘mega-breccia’. The Hwangsan Tuff and AVdb are the predominant units exposed at surface within the Seongsan district. Age dating of least altered Hwangsan Tuff (sample location ca. 10km away from Seongsan district to escape alteration) indicates an age of 86.4±1.8Ma to 84.5±1.3Ma. Locally, altered Hwangsan tuff has an age of 83.1±1.6Ma, although this may reflect the age of alteration in the district rather than formation. Hydrothermal sericites and alunites from the Seongsan (80.9±1.2Ma to 78.1±1.1Ma) and Ogmaesan (81.4±1.0Ma to 79.0±1.2Ma) high-sulfidation epithermal deposits of the district show a combined range from 81.4±1.0Ma to 78.1±1.1Ma. Apparent ages of alunites are older than those of sericites. The AVdb unit unconformably overlies the tuff members, and has an age of 74.2±1.7Ma to 72.5±1.3Ma. All these ages were obtained by the $^{40}K/^{40}Ar$ method (Kim & Nagao, 1992).

1.3.1.5 Tectonics of the area during the Late Cretaceous to Early Tertiary

Orogenic events that have influenced the Yuchon Group are limited to the Bulguksa Orogeny. The *Bulguksa Orogeny* occurred during the Late Cretaceous and Early Tertiary. During this time, intensive volcanism and plutonism was taking place coincident with low-angle subduction of the Kula Plate (Fig. 1-10 C). This includes the eruption and deposition of the Yuchon Group rocks and emplacement of the Bulguksa Series granitoids. During this time, wide-scale deformation was negligible except for normal and strike-slip faulting. Far to the north, transcurrent movement on the Tan-Lu fault (Fig. 1-10) had stopped in the Late Cretaceous, changing to extensional movement. The collision of the Indian and Asian Plates (Fig. 1-10 C) caused tectonic inversion of the transtensional basins (Chough et al., 2000). In the south towards coastal East Asia, the magmatic activity during the Late Cretaceous was migrating, progressively getting younger toward the southeast of Korea. From this, some postulate that proto-Japan was beginning to drift to the southeast with magmatic activity following this plate movement. All of these lines of evidence show that from the Late Cretaceous, Korea was beginning to experience minor extension.

The Seongsan district is located within Cretaceous volcanic rocks of the Yuchon Group, which are found across southern Korea, but are significantly more voluminous in the southeastern part than locally within the Seongsan district. This spatial distribution implies that the volcanic front (the trenchward limit of volcanoes, typically parallel to the trench axis; Tatsumi & Eggins, 1995) was most likely towards the southeast rather than the volcanic front occurring locally. During the Cretaceous, the subduction zone was eastward of Japan and examination of Figure 1-12 (and other tectonic reconstructions by Chough et al., 2000) shows that Japan hosts a trench-side volcanic front, and southeast Korea hosts a backarc-side volcanic front (ca. 150km from the subduction zone), therefore the area represents a double volcanic chain. The Seongsan district (ca. 200km from the subduction zone) occupies an inboard location with respect to the backarc volcanic front. Japan hosts the trench-side volcanic front. Broad volcanic chains with multiple volcanic fronts are generally the result of low-angle subduction (e.g. west coast Pacific: northeast Japan and Kamchatka, Tatsumi & Eggins, 1995) whereas single narrow volcanic chains are the result of high-angle subduction (e.g. east coast Pacific: parts of the Andes and Central America, Tatsumi & Eggins, 1995).

1.3.1.6 Plutonic activity during the Late Cretaceous to Early Tertiary

The Yuchon Group is intruded by the Bulguksa Series granitoids. These were emplaced during the *Bulguksa Orogeny* between the Late Cretaceous and Early Tertiary, generally emplaced at depths of less than 2-3km (Tsusue et al., 1981). The Bulguksa Series granitoids include 1. Jiyoungsan granite, a medium grained hornblende-biotite granite with a fine to medium grained, weak to moderately developed porphyritic texture, dated at 81.5±4.0Ma; 2. Weolchulsan granite, a medium to coarse-grained porphyritic biotite granite, dated at 81.2±4.0Ma & 77.0±1.2Ma; 3. Weolgangdu quartz porphyry dated at 77.9±3.8Ma & 75.0±2.8Ma; and 4. Jangseong granite porphyry dated at 71.8±3.6Ma. The Bulguksa Series granitoids are the plutonic equivalent of the Haenam Formation. All these ages were obtained by the $^{40}K/^{40}Ar$ method (Kim & Nagao, 1992). Refer to Chapter 2, Section 2.2.6 for a discussion on these dates. Previously published $^{40}K/^{40}Ar$ age data (Kim & Nagao, 1992) on host rocks and Cretaceous granitoids within the Seongsan district and more regionally and previously dated alteration sericites and alunites from the Seongsan and Ogmaesan deposits are shown in Figure 1-14.

1.3.1.7 Tectonics of the area after the Cretaceous

The presence of thick conglomerate beds at the base of the Neogene seems to indicate some tectonic instability during early Miocene time. This is tentatively referred to as the Yongil Disturbance (Lee, 1987). Additional evidence for this obscure event is limited to post-Cretaceous brittle faulting generally restricted to southeast Korea, indicating that this was not a widespread tectonic event. This is thought to be closely related to the opening of the Sea of Japan. Quaternary tectonic activity is limited to volcanism related to intraplate hotspots such as Cheju Island, ca. 150km south of the Seongsan district.

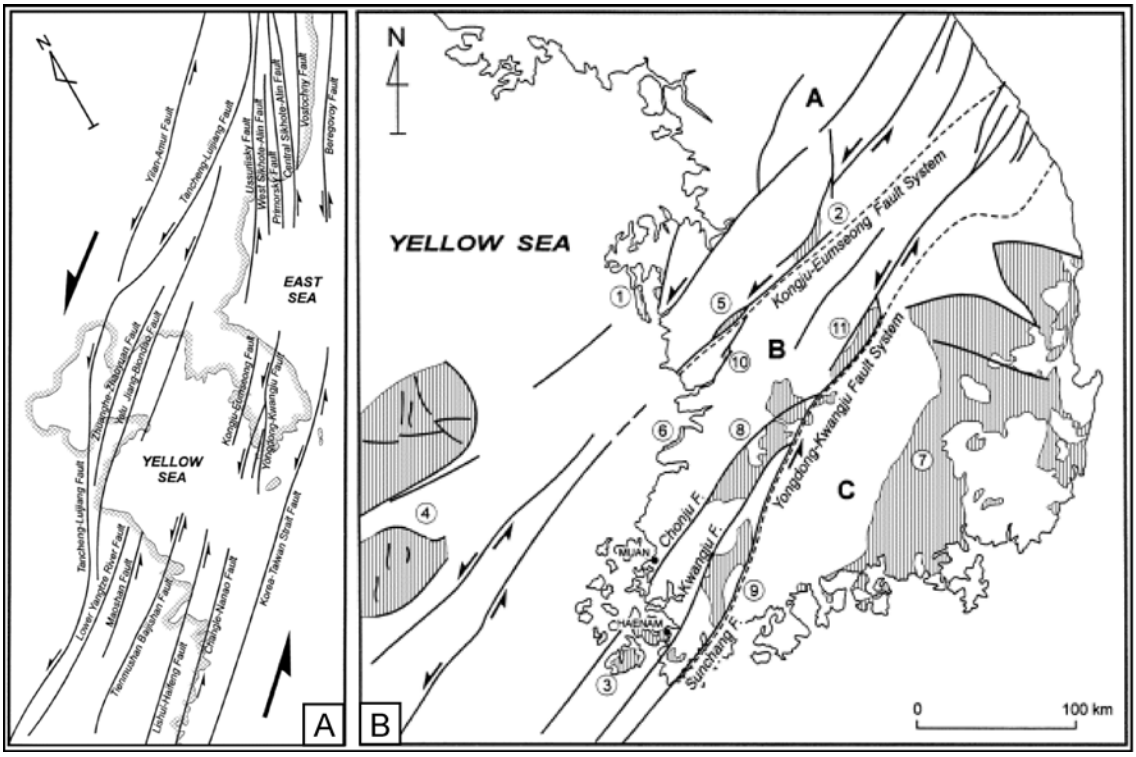


Fig. 1-11 Cretaceous tectonics of Korea. This figure roughly coincides in time with high-sulfidation activity in the Seongsan district. **A**: Cretaceous sinistral strike-slip fault systems of Far East Asia, and **B**: Cretaceous sedimentary basins of the Korean peninsula, the Kyonggi massif (labelled '**A**'), the Okchon Fold Belt (labelled '**B**'), the Yongnam massif (labelled '**C**') and major regional scale fault systems. Numbers and hatching pattern refer to Cretaceous sedimentary basins. The Haenam basin (labelled as '**3**') in the southwest is host to the Seongsan district. The Haenam basin is bounded to the west and east by the sinistral strike-slip Chonju and Kwangju Faults. Dashed lines represent terrane boundaries between the Kyonggi massif, the Okchon Fold Belt and the Yongnam massif ('A', 'B' and 'C'); mostly these boundaries are fault bound. From Lee (1999).

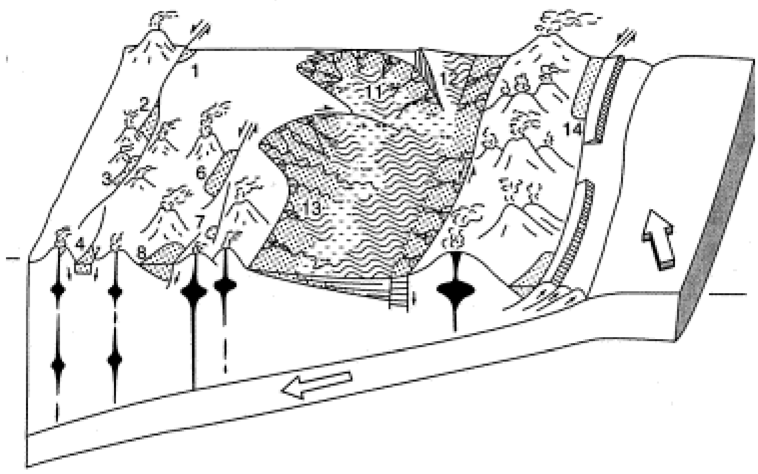


Fig. 1-12 Schematic cross section looking north showing Cretaceous back arc tectonic setting for the Chollanam Province. The tectonic setting was sinistral strike slip under a transtensional regime with the development of pull-apart basins. This tectonic regime was followed shortly after by a transpressional regime. During the Late Cretaceous to Early Tertiary, Korea began to experience minor extensional tectonics. By the Miocene the volcanic arc in the right of the figure, which later evolved into modern day Japan, began to drift eastward as the opening of the Sea of Japan begun. From Chough et al. (2000).

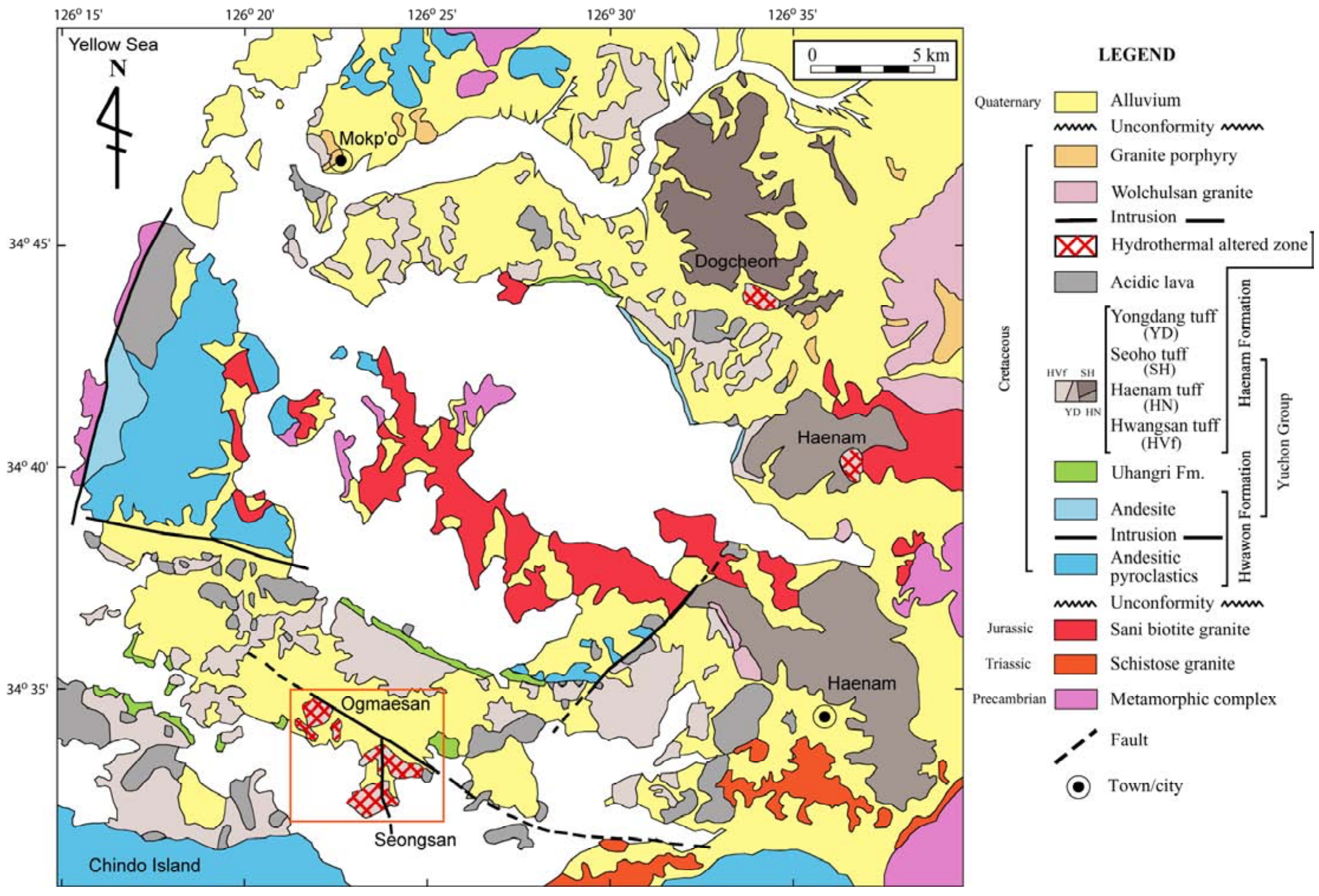


Fig. 1-13 Regional geology of the broader area around the Seongsan district. This figure is at approximately the same scale as Figure 1-8B. The box outline around Seongsan and Ogmaesan shows the area illustrated in Figure 1-8C. Geology and structure within this figure are from Koh (1996).

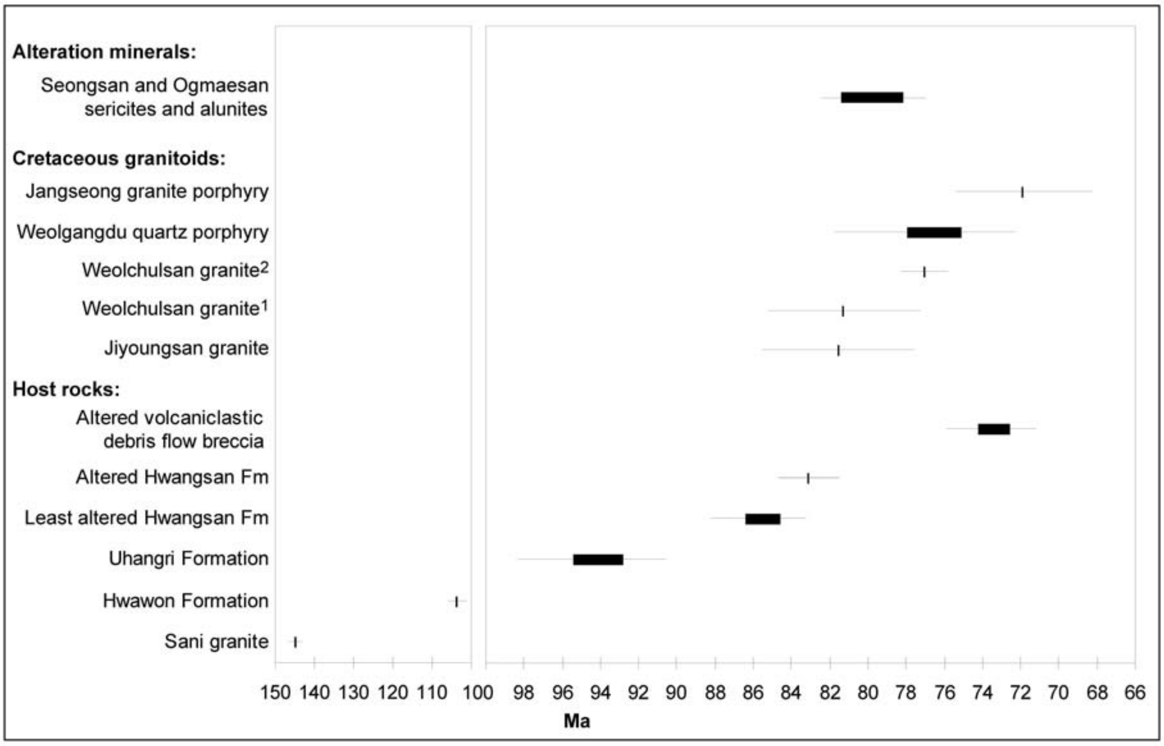


Fig. 1-14 Compilation of previous $^{40}K/^{40}Ar$ age data by Kim & Nagao (1992) grouped by host rocks and Cretaceous Bulguksa granitoids within the Seongsan district and more regionally and previously dated alteration sericites and alunites from the Seongsan and Ogmaesan deposits (combined this figure; see Chapter 4 for further detail). **[1]** and **[2]** refer to two ages obtained for the Weolchulsan granite by Kim & Nagao (1992).

Note: Thin vertical dash represents one age date with corresponding thin horizontal line representing error for that data. Thick horizontal line represents multiple age data range for a given unit with thin horizontal line representing total error for that data range.

1.3.2 Metallogenic overview of Korea, with a focus on the south-west

The Au mining history of South Korea extends over 1,000 years and in modern times, Au production has predominantly come from hypothermal or, more commonly, mesothermal veins (Shimazaki et al., 1981). These mesothermal vein systems are associated with deeper level intrusives of the Daebo series granites, most commonly found in the north and central parts of South Korea, and have been referred to as “Korean-type” Au-Ag deposits (Shelton et al., 1990). Epithermal Au-Ag deposits are scarce in Korea. Where present, they are associated with the shallow level intrusives of the Bulguksa Series (Sections 1.3.1.5 and 1.3.2.2) and hosted in hypabyssal and volcanic rocks that are restricted to the southern part of the Korean peninsula.

1.3.2.1 Jurassic to Early Cretaceous

Deposits related to Jurassic to Early Cretaceous Daebo granitoids include gold-silver, lead-zinc, tungsten-molybdenum-tin, fluorite, magnetite and manganese types (Kim & Lee, 1983). Ten discrete Au-Ag metallogenic provinces have been identified based on known occurrences of Jurassic to Early Cretaceous Au-Ag deposits (Fig. 1-15). Perhaps the potential for hypothermal to mesothermal vein mineralisation has not been recognised within the southern parts of Korea due to the extensive volcanic rock cover as compared to the limited or no cover in the central and northern parts of South Korea.

1.3.2.2 Late Cretaceous to Early Tertiary

Within the Late Cretaceous to Early Tertiary rocks, identified metallogenic provinces include gold-silver, manganese, lead-zinc, copper, tungsten-molybdenum, magnetite and pyrophyllite (Fig. 1-15; Kim & Lee, 1983). The ‘pyrophyllite’ metallogenic province is a generic term similar to the ‘Roseki’ type deposits of Japan. These provinces are characterised by kaolinite-dickite, alunite, pyrophyllite and other clay deposits.

Only one Late Cretaceous to Early Tertiary Au-Ag metallogenic province has been identified. This Au-Ag province is represented by the Tongyoung underground vein-type low-sulfidation epithermal Au-Ag deposit (Fig. 1-15) and is coincident with one of the pyrophyllite metallogenic provinces.

The Tongyoung deposit is located on the southern central coast of the Korean peninsula ca. 150km to the east of the Seongsan district. Except for the recently discovered Eunsan Au-Ag deposit within the Seongsan district, Tongyoung is the only other significant Au-Ag resource associated with a low-sulfidation epithermal system identified in Korea to date (Shelton et al., 1990). Tongyoung is hosted by Cretaceous volcanic rocks of the Yuchon group, as is the Seongsan district. The Au ore body is comprised of veins generally less than 1.2m wide that extended over a strike length of approximately 800m and down dip 250m. The deposit was first mined in 1916 and intermittent production of approximately 200,000oz of Au took place until 1989 when the mine closed. Average grades were reported to be 12ppm Au and 135ppm Ag. Sericite from an alteration halo adjacent to a Au-Ag-bearing quartz vein in the mine yielded a $^{40}K/^{40}Ar$ date of 72.9±1.2Ma (Shelton et al., 1990).

All of the Late Cretaceous to Early Tertiary metallogenic provinces are inferred to be associated with Late Cretaceous to Early Tertiary Bulguksa Series granitoids and/or various hypabyssal and volcanic rocks that are restricted to the southern part of the Korean peninsula.

In total, there are five identified pyrophyllite metallogenic provinces, and one of the most significant in terms of commercial clay production is that which corresponds to the Chollanam Province. The Seongsan district is centrally located within this pyrophyllite metallogenic province. Advanced argillic alteration at Seongsan is the direct result of hydrothermal alteration in a high-sulfidation epithermal setting. The Au-Ag producing low-sulfidation epithermal systems of the Seongsan district comprise a new Au-Ag metallogenic province in South Korea. Whether the Seongsan district will become a major Au-Ag producing area is yet to be fully realised, but what it has shown is that there is still potential for new Au-Ag discoveries to be made.

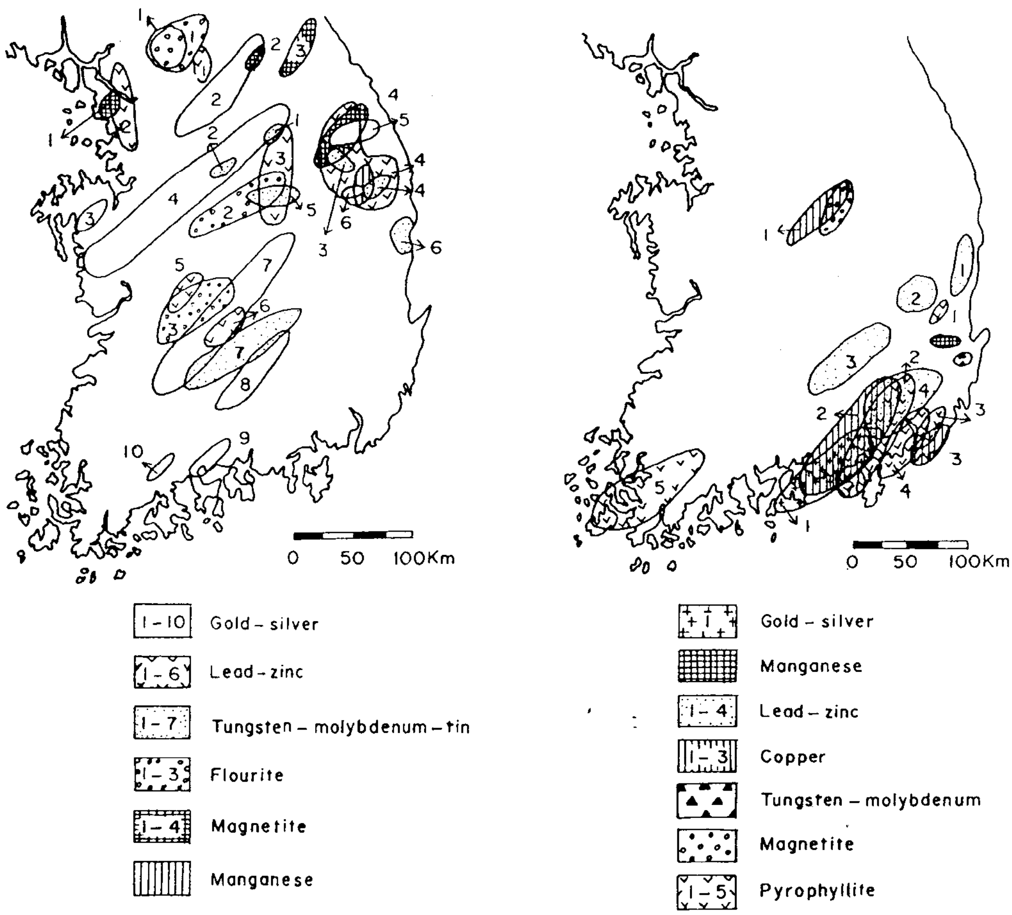


Fig. 1-15 Metallogenic provinces of the Jurassic to Early Cretaceous (left) and Late Cretaceous to Early Tertiary (right). From Kim & Lee (1983).

Note: the Seongsan district has previously only been identified as occurring within a pyrophyllite metallogenic province, but the recently recognised low-sulfidation systems that have recoverable Au and Ag has identified a new Au-Ag province in this part of South Korea.

1.4 PREVIOUS WORK WITHIN THE SEONGSAN DISTRICT

The dominant lithostratigraphic unit in the Seongsan district which hosts the various epithermal systems is a complex suite of sedimentary rocks, sub-volcanic intrusions and related acid volcanic rocks collectively named the Haenam Formation (Koh, 1996). This unit has previously received little direct field-oriented geological investigation in the Seongsan district. In 1929, there was a regional geological survey over the area at 1:50,000 scale by the Geological Survey of Choson (Kinosaki, 1929). The dissertations of Kim (1991) and Koh (1996) briefly cover aspects of local geology but their primary focus was on the geochemical characteristics of the high-sulfidation hydrothermal systems. Park et al. (1997) briefly investigated the geology of the district. Their primary focus was on developing a better understanding of the origin of the volcaniclastic breccia that unconformably overlies the Haenam Formation, which they termed 'megabreccia' (cf: 'AVdb'; Chapter 2, Section 2.2.3.3). Dr Tony Reedman (pers. comm. Nov. 2003) from the British Geological Survey, working with KIGAM (Korea Institute of Geoscience And Mineral resources), was undertaking regional mapping of the broader area at 1:50,000 during November 2003 aiming at improving on the earlier work of Kinosaki (1929).

Koh et al. (2000) concluded that the Chollanam Province, of which Seongsan district is part, is characterised by alunite-kaolin-quartz±pyrophyllite±diaspore deposits formed between 81.4Ma to 70.1Ma with a genetic relationship to silicic lava domes and are hosted within Late Cretaceous volcanic and granitic rocks. Furthermore, Koh et al. (2000) characterised the igneous rocks of the Chollanam Province to a high-K calc-alkaline series formed in a continental margin volcanic arc above an active subduction zone. Key geochemical criteria on which this conclusion was based include the enrichment of the volcanic rocks in crustal components such as K, La, Ce, Sm, Nd and B; high (La/Yb)cn ratios (ca. 22.67:1); and high initial $^{87}Sr/^{86}Sr$ ratios of 0.708 to 0.712, which indicate a source that is at least older partly crustal material.

Unlike the Haenam Formation, the sedimentary rocks of the underlying Uhangri Formation have received more in-depth analysis including both sedimentological and palentological research. Sedimentological research on the type-section of the Uhangri Formation 3km north of this study area has indicated that the sequence generally shows a fining-upward trend with a transition from alluvial fan fringe, to coarse-grained subaqueous deltas, to shallow lake facies (Chun & Chough, 1995; Fig. 1-16). This transgression was inferred to be due to continuous subsidence related to continental rifting (Chun & Chough, 1995). Palaeontological research has shown it to locally contain footprints and trackways of dinosaurs, pterosaurs, birds and arthropods (Hwang et al., 2002) and plant fossils (Chun & Chough, 1995).

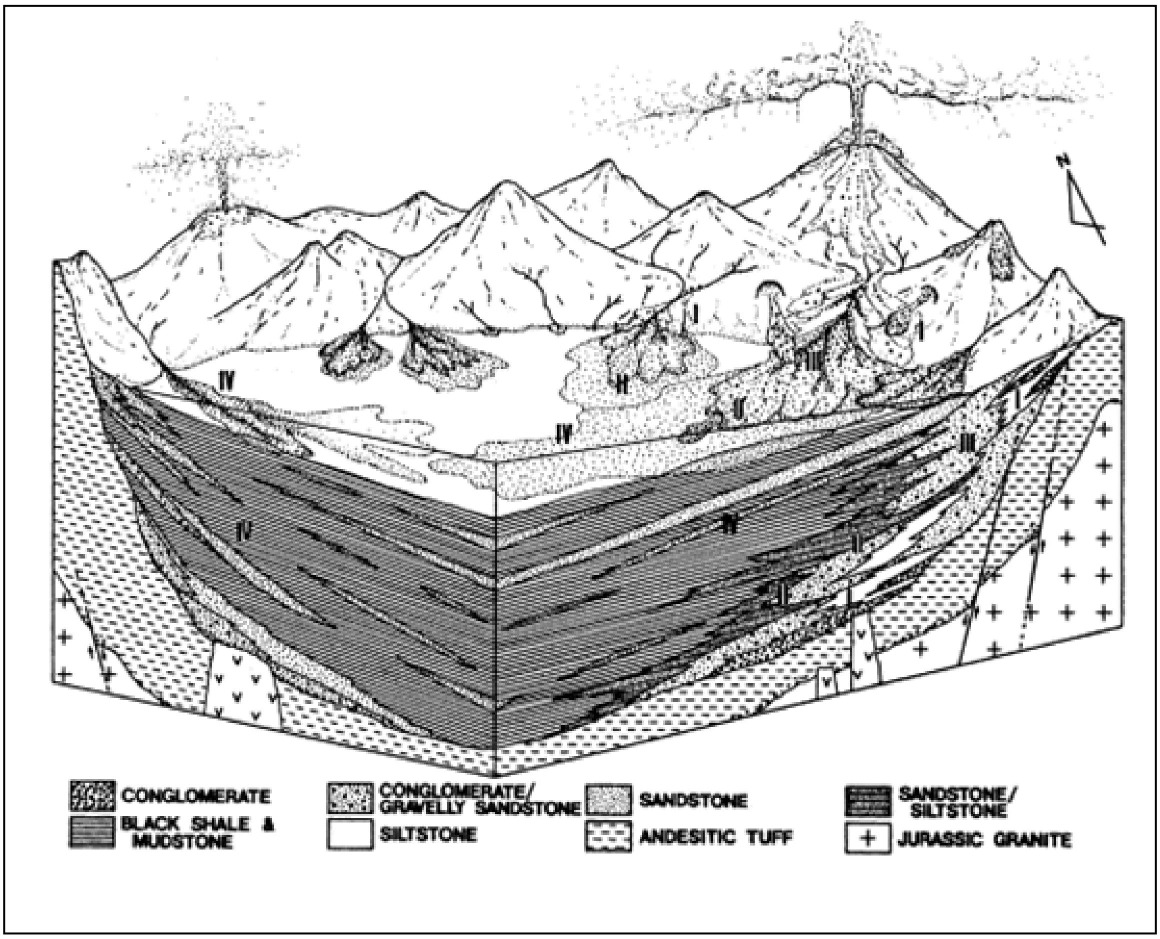


Fig. 1-16 A schematic representation of possible paleo-setting corresponding to the transition between the deposition of the Uhangri Formation and the deposition of the Haenam Formation. From Chun & Chough (1995).

Despite the lack of geologically-focussed field investigations in the Seongsan area, numerous workers have thoroughly investigated the geochemical characteristics of the clay-sulfate-silica deposits, including the zones of advanced argillic alteration associated with the high-sulfidation systems, within the Seongsan district (Kim et al., 1990; Kim, 1991, 1992b, a; Kim et al., 1992; Kim & Nagao, 1992; Kim & Kusakabe, 1993; Yoon, 1993, 1995; Koh, 1996; Koh & Chang, 1997; Koh et al., 2000). Only a few of these previous workers have recognised the high-sulfidation style Au mineralisation in the district. Kim (1992a), Kim & Kusakabe (1993) and Yoon (1993, 1995) confirmed the association of Au mineralisation within the clay-sulfate deposits as a product of the hydrothermal high-sulfidation style alteration.

Analysis of the geologic setting of the high-sulfidation epithermal systems in the Seongsan district is currently limited to the suggestion by Cha & Yun (1988), and supported by Kim & Nagao (1992) and Koh et al. (2000), that they are localised along the margins of a caldera in the Cretaceous volcano-sedimentary host rocks (Fig. 1-17). This suggestion is based on the location of high-sulfidation systems around an apparent circular feature. Inference of a caldera setting by these workers may also reflect general genetic models of high-sulfidation systems (e.g.: Rytuba, 1994) rather than specific evidence of a caldera setting such as radial and ring faults, and local explosive volcanic geology that would support a caldera setting (discussed further in Chapter 6).

Kim (1992b, 1992a) and Kim et al. (1992) investigated the district specifically looking at hydrothermal alteration related to Cretaceous felsic magmatism. Kim (1991, 1992b) produced highly simplified alteration maps at approximately 1:20,000 scale of selected clay deposits.

Kim & Nagao (1992) undertook $^{40}K/^{40}Ar$ age dating of alteration minerals (alunites and sericites) and a number of host volcanic and igneous rocks from clay deposits in southwest Korea, including the Seongsan district. Of particular interest is that the timing for the formation of the Seongsan district clay-sulfate deposits (81.4 to 78.1Ma) was later than the host rocks (86.4 to 83.1Ma) indicating that the hydrothermal alteration was not associated with emplacement of the host volcanic rocks but that later intrusions (81.5 to 77.1Ma) were a potential source for the hydrothermal fluids.

Kim & Kusakabe (1993) undertook an oxygen and hydrogen isotope study of hydrothermally altered minerals from clay-sulfate deposits over the Seongsan district. They concluded that the Seongsan clay-sulfate deposits formed at temperatures of 224ºC to 281ºC and the Ogmaesan deposits formed at temperatures of 175ºC to 250ºC. Furthermore, they infer that the kaolinite and alunite are of a hypogene origin.

Koh (1996) and Koh & Chang (1997) investigated the major, trace and rare earth element, stable isotope (S, O & H) and fluid inclusion characteristics of the Seongsan clay-sulfate deposits. They also looked at the associated Au mineralisation previously identified by Kim et al. (1992) and concluded that the geochemical characteristics of the Seongsan clay-sulfate deposits are very similar to those of epithermal Au deposits.

Most recently, Choi et al. (2005) investigated 'epithermal Au-Ag systems of Korea', with the aim of providing a general overview of the genesis of epithermal deposits in Korea and relating Au-Ag mineralisation to the tectonic evolution of Korea during the Cretaceous. This is the first published account of the low-sulfidation Au-Ag systems within the Seongsan district, other than several internal unpublished company reports by Ivanhoe Mines Ltd. Choi et al. (2005) used two of the epithermal low-sulfidation prospects in the Seongsan district to compare with Au-Ag mineralised systems in central Korea, which more closely resemble mesothermal vein systems. Their investigations were broad-scale and resulted in unsubstantiated conclusions regarding the structural setting of these systems in a caldera. Choi et al. (2005) did not provide specific evidence regarding ore-fluids, precise timing of formation, or the relationship of the low-sulfidation systems to the nearby high-sulfidation systems.

Figures 1-17 to 1-20 are presented to show the previous level of geological mapping in the Seongsan district prior to this study. Figure 1-17 shows the location of high-sulfidation clay-sulfate-silica deposits and the apparent circular feature within the Chollanam Province. This has been named by local workers as the Haenam caldera (Section 2.3.6). Figures 1-18 and 1-19 show geological maps of the Seongsan area, with cross section after Koh & Chang (1997). The geology is dominated by a large intrusive and extrusive rhyolitic dome, Uhangri Formation sediments and overlying volcanic breccia. Figure 1-19 shows surface alteration zoning and fault networks at Seongsan as determined by Koh & Chang (1997). The alteration zonation is described as the result of decreasing acidity and temperature of hydrothermal fluids away from core zones as fluid ascended through rhyolite dome and spread laterally along contacts giving a flattened mushroom shape. Figure 1-20 shows an alteration zonation map of the Ogmaesan mine area based on visual clay interpretations by Kim (1992a). Apart from 1:50,000 scale regional mapping by Kinosaki (1929) and the highly simplified ca. 1:20,000 scale alteration maps by Kim (1991, 1992a), no other field-based investigations have previously attempted to map the Ogmaesan system.

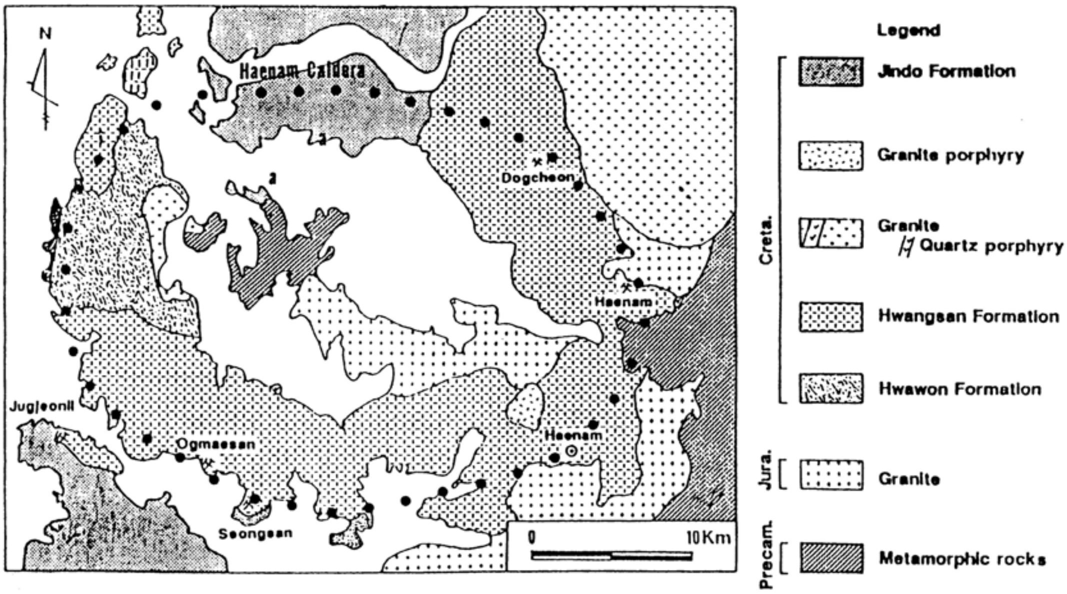


Fig. 1-17 The most commonly inferred position for a potential Haenam caldera and location of high-sulfidation clay-sulfate-silica deposits within the broader region, from Kim & Nagao (1992). For a more thorough review of a caldera setting in the Seongsan district, refer to Chapter 2, Section 2.3.6.

Note: Kim & Nagao (1992) use a different stratigraphy for the area than that of Koh (1996) and this study. Therefore, unit names in their legend are different. Regardless, this figure is only intended to highlight the location of the inferred Haenam caldera.

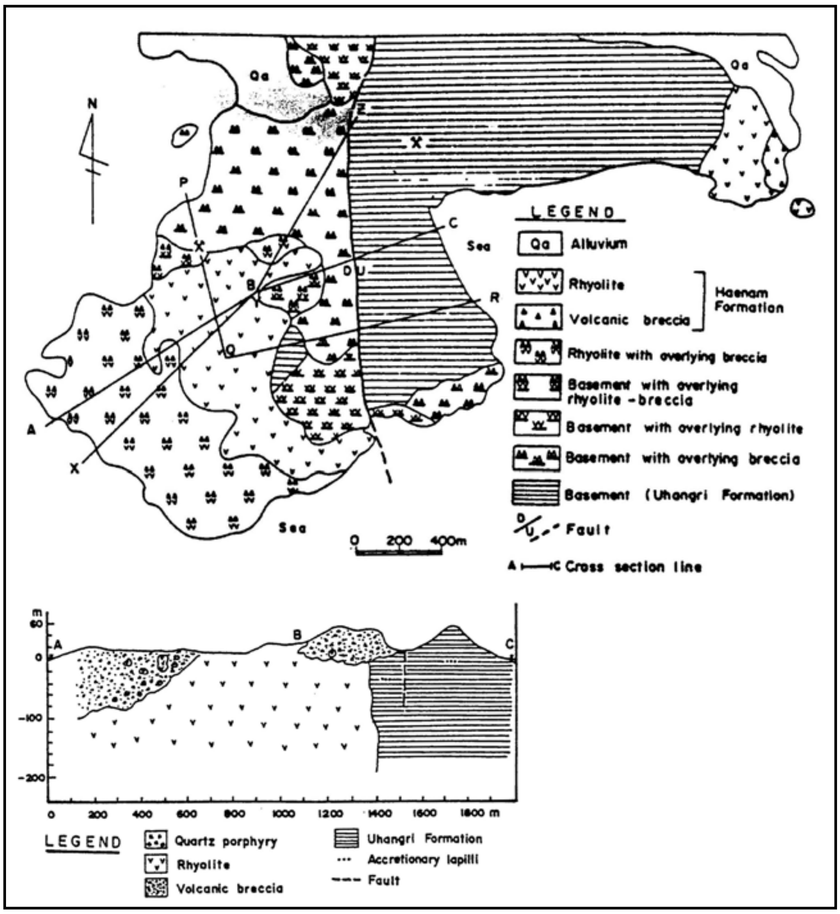


Fig. 1-18 Surface geological map of the Seongsan area and cross section as determined by Koh & Chang (1997). Geological units used in this map and section are unusual (see legend), and the structural mapping is limited.

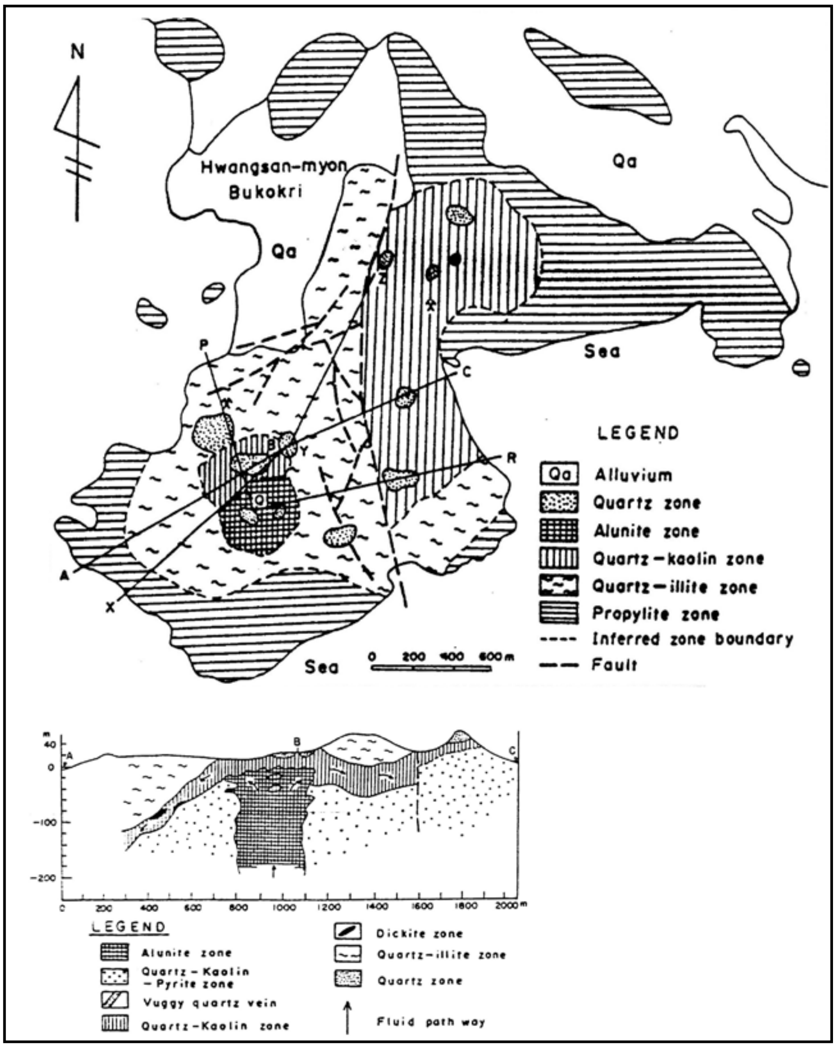


Fig. 1-19 Alteration and structural mapping of the Seongsan area after Koh & Chang (1997).

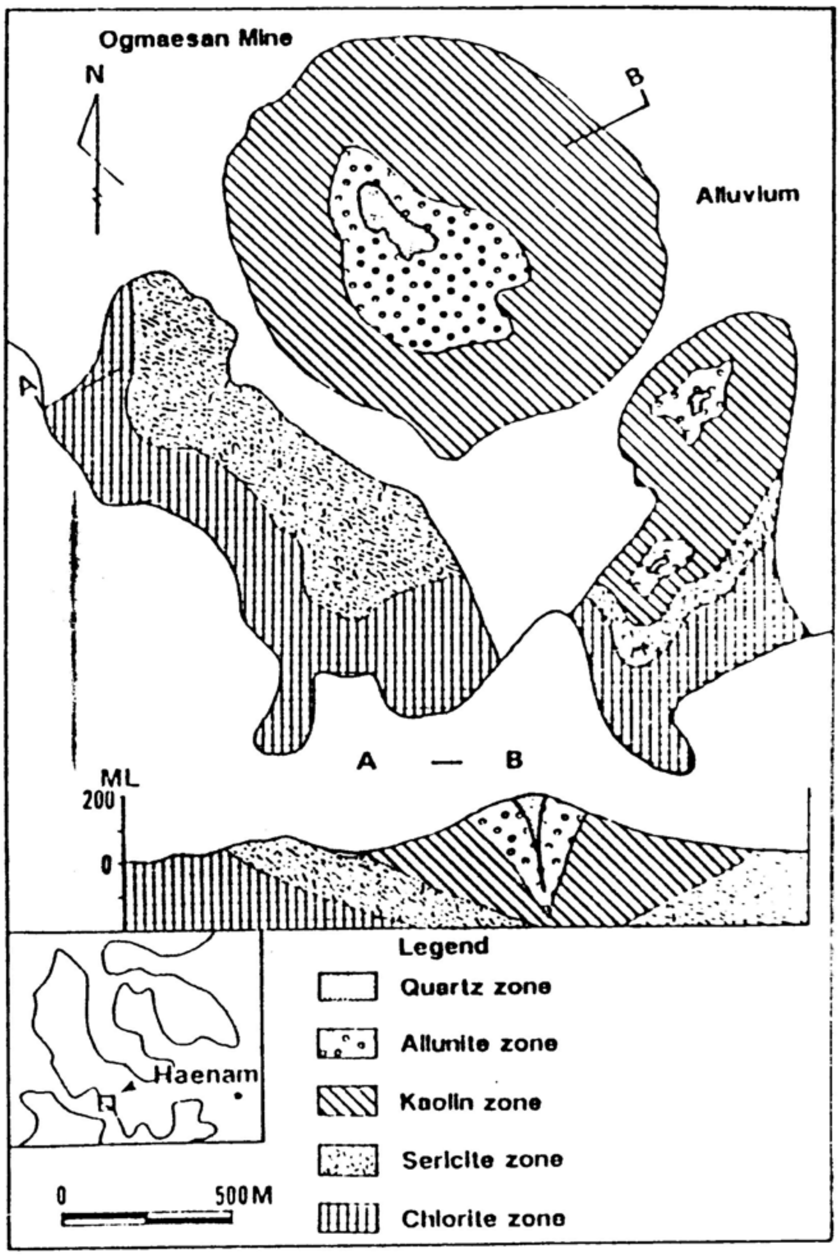


Fig. 1-20 Alteration zonation map of the Ogmaesan mine area after Kim (1992a).

A brief note on the transliteration of Korean terms and names

Many terms and names used throughout this thesis are local names or names derived from local areas of significance. The Korean language is represented by the writing system known as Hangul that currently consists of 14 consonants and 10 vowels (and many vowel combinations as diphthongs). Due to the number of vowels and diphthongs, various transliteration rules have been used in an attempt to best represent the Korean language in a Romanised form. Revisions of transliteration rules gives rise to a situation where there may be different spellings for the same name or term, e.g.: the second largest city in South Korea, Busan is equally represented as Pusan; or Kyongsang Basin has also been known as the Gyeongsang Basin; and the Yuchon Group has also been know as Yucheon Group. This obviously presents a multitude of problems when undertaking extensive and detailed research as most names can vary between different publications due to various transliteration rules at the time.

This thesis has attempted to represent the currently accepted version for the Romanised transliteration of Hangul, but some errors may be present.