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As a continuum of deposit styles, there is a spatial and temporal relationship between epithermal quartz gold-silver and carbonate-base metal gold systems. This is interpreted to represent the variation during the mixing of upwelling intrusion-derived mineralized fluids with either: CO_2-rich ± acid sulfate waters (to produce carbonate-base metal systems), or cool dilute oxidizing ground water (to produce epithermal quartz gold-silver vein systems).

Karangahake in New Zealand, and Misima in Papua New Guinea represent examples of a continuum from carbonate-base metal gold mineralization at depth, to epithermal quartz gold-silver mineralization at progressively shallower crustal levels. Maniape and Kelian represent examples of horizontal zonations from carbonate-base metal gold mineralization formed proximal to an inferred intrusion source, to the quartz gold-silver mineralization in more distal settings. At Mt. Kare, the quartz-roscoelite alteration occurs overprints of the carbonate-base metal gold mineralization. In many systems, the epithermal quartz gold-silver mineralization forms late in the paragenetic sequence (e.g., Maniape), or occurs in late stage breccia zones and veins which cut the carbonate-base metal system (e.g., Zone VII at Porgera). Petrological data at Maniape demonstrates that the two events can be initially contemporaneous, although the epithermal quartz gold-silver mineralization here post-dates much of the carbonate-base metal mineralization.

Some epithermal quartz gold-silver deposits, characterized by banded quartz veins (e.g. Tolukuma and Cracow), are similar to the adularia-sericite epithermal gold-silver systems which occur in New Zealand and Japan (Chapter 8). However, the epithermal quartz gold-silver systems form within magmatic arc environments and are associated with high level intrusions and fluidized or phreatomagmatic breccias. Telluride-rich phases are common in the epithermal quartz gold-silver systems and gold mineralization is intimately related to illite, chlorite and kaolin clays, or with carbonates, in the same manner as the epithermal gold mineralization at Mt. Kare, Porgera and Maniape. On the other hand the adularia-sericite epithermal gold-silver systems form in back-arc basins and are spatially and genetically related to felsic volcanics. These deposits generally lack associations with high level intrusions, typically contain eruption (or phreatic), not phreatomagmatic breccias, and the gold mineralization is associated with selenides rather than tellurides (Table 7.1).

SEDIMENT HOSTED REPLACEMENT GOLD DEPOSITS

CHARACTERISTICS

Sediment hosted replacement gold deposits, also termed Carlin-type gold deposits from where they were first described, have been major gold producers in the western U.S. (98.8 million ounces discovered; Singer, 1993). Most deposits lie along deep crustal fracture systems which define the Carlin and Battle Mountain Trends (Madrid

TABLE 7.1 Distinction between adularia-sericite epithermal and epithermal quartz gold-silver deposits

	Adularia-Sericite-Epithermal Gold-Silver	Epithermal-Quartz Gold-Silver
Setting	Back-arc rift / basin	Magmatic arc
Association	Not obvious intrusion, felsic volcanics commonly present	Intrusions (many alkaline) generally present. Overprinting or subjacent to carbonate-base metal gold mineralization.
Breccias	Eruption (phreatic)	Diatreme or milled matrix fluidized (phreatomagmatic)
Form	Banded fissure veins, sheeted veins, and less commonly, stockwork veins	Fissure veins, breccias, and ore shoots common
Alteration:		
Vein	Quartz, adularia, quartz pseudomorphing platy carbonate	Quartz, chlorite, illitic clay, local roscoelite
Wall rock	Illite, illite-smectite, kaolinite, chlorite	Illite, illite - smectite, kaolinite, chlorite
Ore minerals	Pyrite >> chalcopyrite > sphalerite, galena Ag-sulfides and sulfosalts	Pyrite marcasite, >> sphalerite, galena,chalcopyrite Ag sulfosalts ± Ag sulfides local hypogene hematite
Metals:		
Primary	Au : Ag high to bonanza grades	Au : Ag bonanza grades common
Accessory	Se	Te

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and Roberts, 1990). Significant new discoveries within the Carlin Trend include the Betze-Post and Meikle ore systems (Bettles and Lauha, 1991), with production of 7.1 million ounces and reserves of 28 million ounces of gold at the end of 1994 (Volk et al., 1995). Reviews of this style of gold mineralization by Bagby and Berger (1985), Sawkins (1984), Sillitoe and Bonham (1990), Berger and Bagby (1991), and Kuehn and Rose (1995) present geological models for this deposit type. Critical in the development of these models has been the recognition of similar deposit types in other settings (e.g., Bau, Sarawak; Wolfenden, 1965; Sillitoe and Bonham, 1990: China; Cunningham et al., 1988: Melco and Barney's Canyon deposits, Bingham District, U.S.; Babcock et al., 1992: Mesel, North Sulawesi; Indonesia; Turner et al., 1994; Garwin et al., 1995: and elsewhere in the eastern and western Pacific Rim, G. Corbett and T. Leach, unpub. data; Gemuts et al., 1996: Fig. S.1).

Aspects of sediment hosted replacement gold deposits discussed more fully in the above reviews include:

- Host rocks, described as silty carbonaceous carbonate, carbonate-bearing shale, dolomite and limestone.
- Structural settings, characterized by extension, including normal faults, common doming, and local caps of impermeable units (Berger and Bagby, 1991). Back-arc settings appear to represent conducive environments.
- Metal association of high fineness gold, and enrichments in As, Hg, Sb, Ba, and Tl. Some examples (e.g., Bau, Sillitoe, and Bonham, 1990) are enriched in base metals. Many are metallurgically difficult because of arsenic in the ores.
- Magmatic association is commonly represented by felsic dikes which are indicative of the inferred distal relationship of gold mineralization to intrusion source rocks (Sillitoe and Bonham, 1990; Berger and Bagby, 1991).
- Depth of formation, which is inferred to be well below epithermal environments (Sillitoe and Bonham, 1990; Kuehen and Rose, 1995).
- Mixing of volatile-rich fluids derived from considerable depth with meteoric fluids is inferred as a mechanism of gold deposition by Kuehen and Rose (1995).

Earlier geological models focused on the depth of formation and initially described these western U.S. deposits as epithermal, but more recently suggest a deeper level of formation (Sillitoe and Bonham, 1990; Bagby and Berger, 1985). The emphasis on the porphyry association by Sillitoe and Bonham (1990), gives a better framework for the comparison of different examples of sediment hosted replacement gold deposits. Based upon proximity to the magmatic source, these workers present a model in which mineralization is zoned away from porphyry Cu-Mo-Au stocks and propose that many of the deposits formed at depths of 2–3 km.

Sediment-hosted gold deposits are suspected to be derived from low sulfidation magmatic fluids (similar to those for quartz-sulfide gold mineralization) which have come in contact with reactive host rocks. These settings distal to the porphyry source are not conducive to skarn formation. Ore textures are similar to those seen in other Pacific Rim systems characterized by leaching of the host rocks by reactive fluids (e.g., alteration in high sulfidation systems) or inferred quartz undersaturated fluids and quenched sulfide deposition (e.g., fluidized breccias at Mesel and Lihir). Extensional tectonism, in particular dilational structures at prospect scale, provide plumbing systems conducive to the transportation of mineralized fluids over considerable distances. We suggest that many deposits feature flow paths in which ore fluids migrated from dilational structures, which localize high-grade structurally-controlled ores, and then into reactive lithologies which may host larger volumes of lower gold grade, in lithologically-controlled ores (Fig. 7.55). The relationship between the Post (structurally controlled) and Betze (lithologically controlled) ore systems at Goldstrike, U.S. (G. Corbett, pers. observations with Barrick geological staff, 1996) and also within Mesel, Indonesia (G.Corbett and T. Leach, unpub. reports, 1993) and Mercur, U.S. (G. Corbett, unpub. report, 1996), provide good examples of these relationships. Analyses of structure and alteration zonation within lithologically controlled ores may point to targets for higher gold grade structurally controlled mineralization.

EXAMPLES

1. **Mesel**, North Sulawesi, Indonesia

Recent work on the Mesel gold deposit provides new data on the controls to the formation of sediment hosted gold mineralization in the southwest Pacific (Turner et al., 1994; Garwin et al., 1995; G. Corbett and T. Leach, unpub. reports). During the exploration by Newmont in the 1980s, traditional stream sediment geochemistry was inhibited by contamination from the extensive workings by pre-World War II Dutch, and recent illegal miners. Reports of silicified outcrops by local villagers resulted in the identification of the discovery outcrop for the Mesel deposit at Hein's Find in 1988 (Turner et al., 1994). Gold production began in 1996 from a resource described by Turner et al. (1994) as 12.25 Mt. of 5.21 g/t Au, and more recently by Garwin et al. (1995) as 7.8 Mt. at 7.3 g/t Au.

Sediment hosted gold mineralization at Mesel is both structurally and lithologically controlled. Structural controls result from the reactivation of structural elements in response to the varying tectonic framework through geological time, and deformation of the cover by reactivation of basement structures. Lithological control is provided by permeable carbonate rock types and enhanced by alteration dolomitization. Andesite sills act as local impermeable caps to the ore-hosting limestone sequence (Fig. 7.56).

Structural controls demonstrate a reactivation of existing structures. Miocene extension on EW structures separated by NW transfer faults, provided an environment for carbonate sedimentation overlying the basement volcanic rocks. Later Miocene collision of the Sula Platform caused a rotation of North Sulawesi through 90° to the present position (Kavalieris et al., 1992; Hamilton, 1979). Compression deformed the cover carbonate sequence and created

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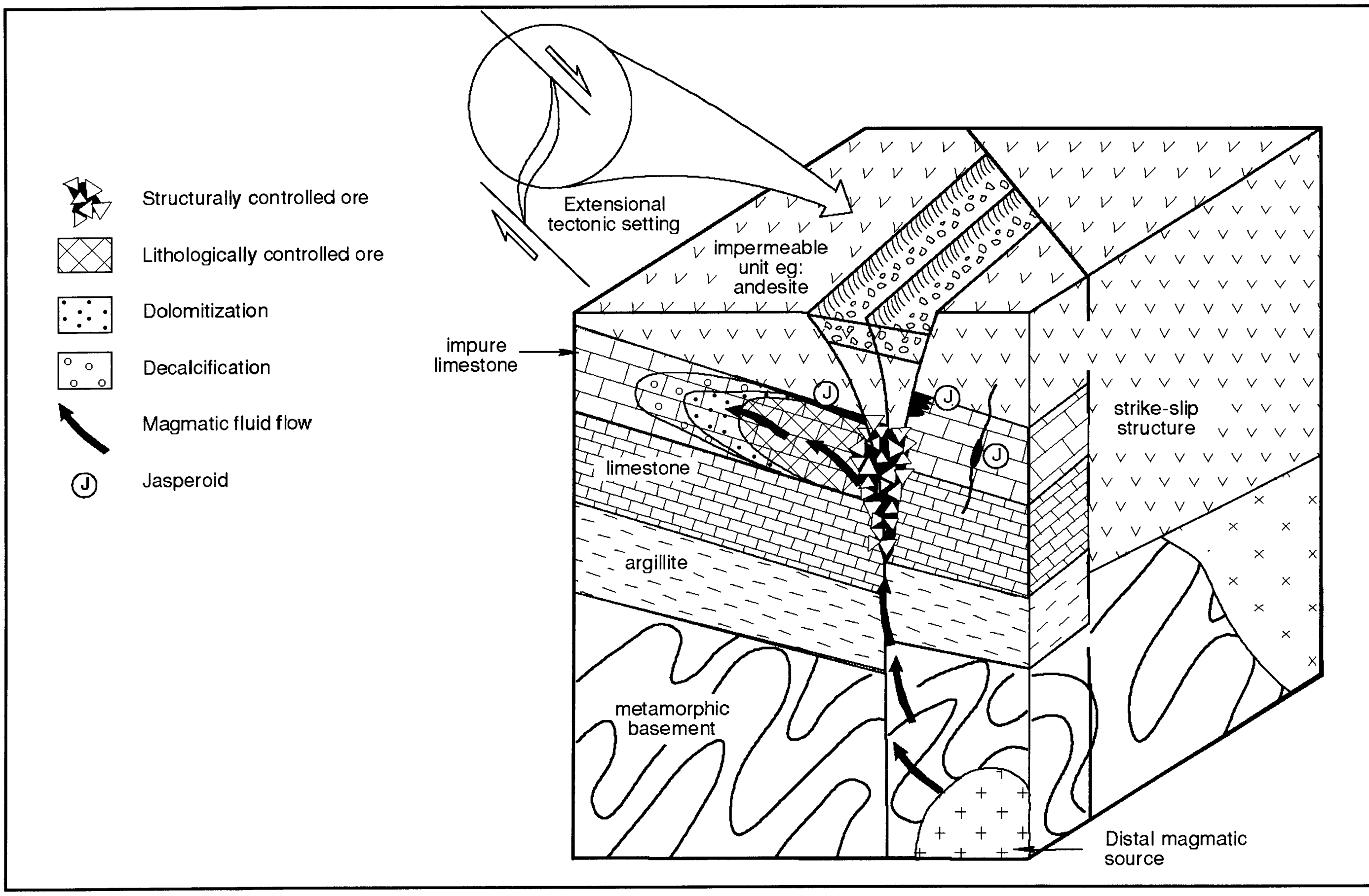

FIG. 7.55 Sediment-hosted replacement gold deposits — conceptual model

flexural slip folds with an EW axis. Subsequent andesite intrusion formed EW-trending oval shaped sills capping plug-like feeders, localized on deep basement NS structures (Fig. 7.56). Intrusion along the folded cover sequence has been aided by slip on mudstone units, and the sills are commonly faulted by high angle EW structures.

A change in the stress regime during the Pliocene promoted mineralization within dilational elements of the same structural framework. Fluid upflow for the Mesel mineralization is hosted in EW structures in the cover sequence, which were dilated by sinistral strike-slip movement on the NW-trending basement transfer structures (Fig. 7.56). NNW structures, likened to domino faults above, localize individual fluid upflow zones at the intersection with dilational faults, and also offset the mineralization during later reactivation (Fig. 7.56).

Alteration and mineralization at Mesel occur within the limestone with local extensions into the overlying andesite. Four main stages of hydrothermal activity are recognized at Mesel (T. Leach, unpub. reports; Garwin et al., 1995; Figs. 7.57, 7.58):

Stage I: Decalcification and dolomitization occur as the replacement of calcite in the limestone by dolomite adjacent to major faults, in sedimentary breccias, and along the contacts with the overlying andesite. The volume decrease associated with the conversion of calcite to dolomite by the dolomitization process creates secondary porosity. Localized zones of decalcification, without dolomite replacement, occur marginal to the dolomitization. It is speculated that less than neutral pH circulating meteoric waters caused this early alteration.

Stage II: Intense silicification, as a result of the filling of open space and replacement of calcite and dolomite, decreases moving away from areas of inferred fluid upflow, towards outflow settings. Vuggy silica rock is speculated to have locally developed through the leaching of carbonates by a less than neutral pH fluid. Alteration in the overlying andesites is zoned from smectite-chlorite at shallow levels, to kaolinite-interlayered clays-gypsum at depth. Kaolinite and illitic clays locally overprint dolomitized limestone, and in places post-date Stage II silicification.

Stage III: The main phase of gold mineralization is associated with quartz-sulfide deposition during polyphasal brecciation of the silicified dolomite and altered limestone. Coarse grained barite was locally deposited with the quartz-sulfide, and in many cases has subsequently been replaced by later quartz. In some cases illite is intergrown with quartz and indicates temperatures of deposition around 200°–250°C. Early sulfides comprise simple, coarse pyrite which is intergrown with dolomite during Stage I

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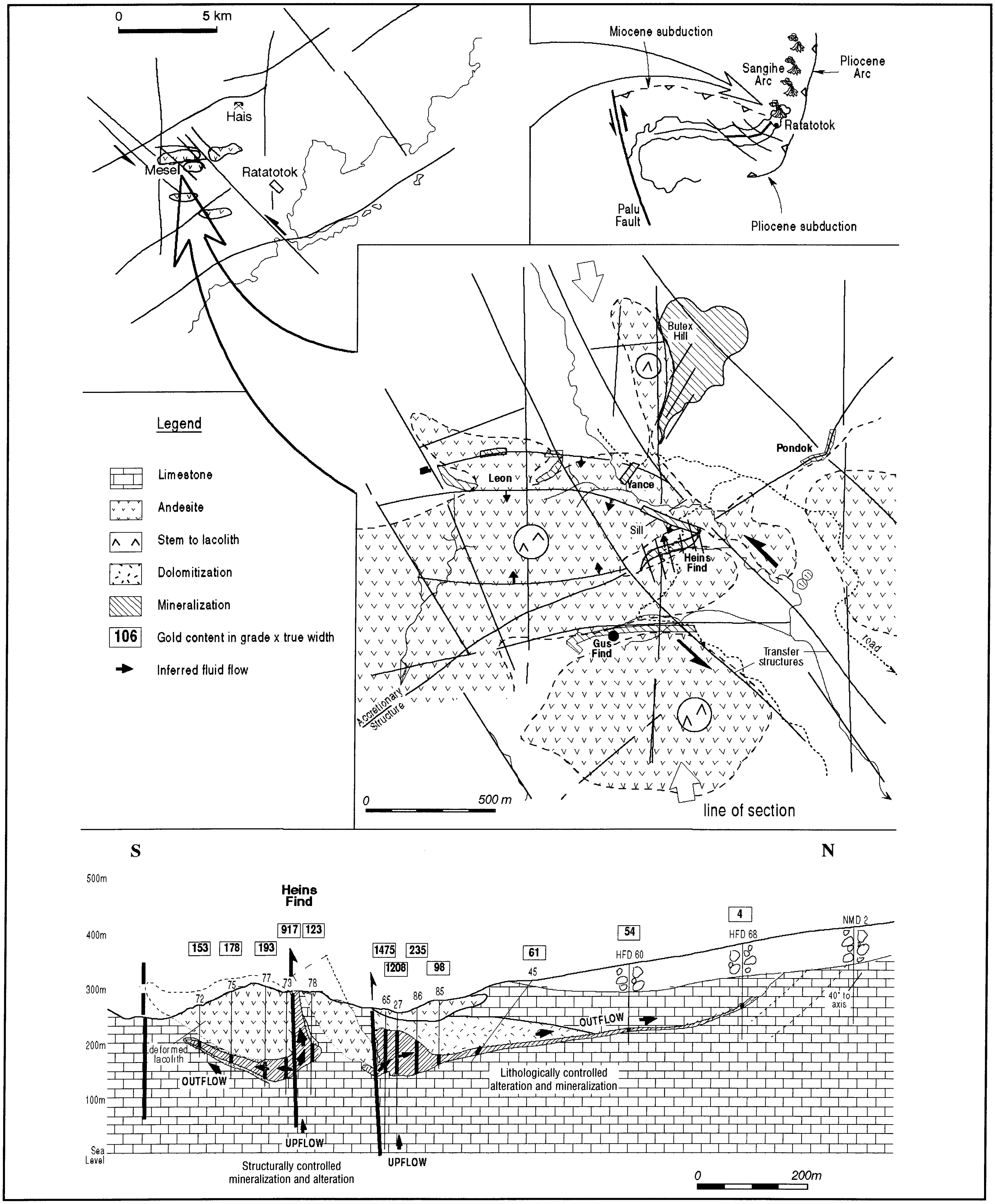

FIG. 7.56 Mesel — structure

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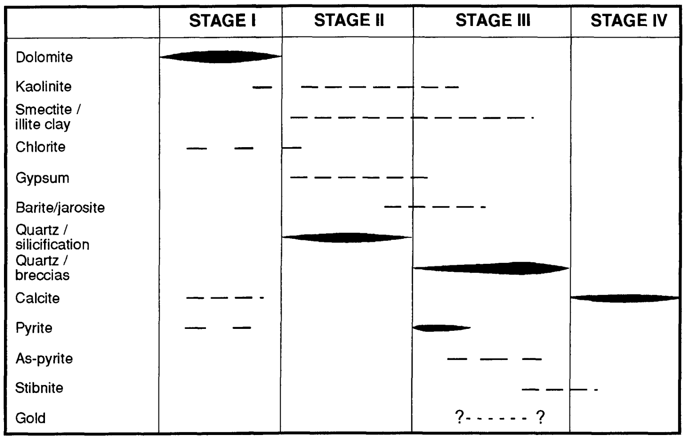

FIG. 7.57 Mesel — paragenetic sequence of alteration, vein development, and mineralization

activity, and with quartz in early Stage III breccias. The pyrite becomes progressively more arsenic-rich during Stage III activity, and here tabular to rhombic arsenical pyrite is intergrown with quartz in breccia matrix, locally grading to arsenopyrite. There is a strong positive correlation between gold grades and arsenical pyrite content. Gold is submicron in size and associated with very fine-grained (<10 micron) arsenical pyrite. Gold grades are highest in the polyphasal silicified breccias proximal to feeder (fluid upflow) structures. Gold contents, measured in terms of thickness x grade, decline rapidly from the upflow zone to lithologically controlled outflow zones constrained below the andesite sills (Fig. 7.56). Pyrite which is commonly intergrown with kaolinite in late Stage III and early Stage IV, is fine-grained and framboidal, and overgrows earlier pyrite, implying rapid cooling following the main mineralizing event. Stibnite occurs as a late sulfide phase associated with both Stage III quartz veins and Stage IV calcite at shallow levels and in zones peripheral to the ore body.

Stage IV: Post-mineral calcite veins transect earlier alteration and mineralization.

A conceptual fluid flow model for gold mineralization at Mesel suggests that the fluid upflows were localized with dilational EW structures, hosted in reactive calcareous sediments and capped by impermeable andesite aquacludes (Fig. 7.58). The lateral fluid flow was facilitated by permeability in the limestone aquifer beneath the andesite aquaclude. Limestone permeability resulted

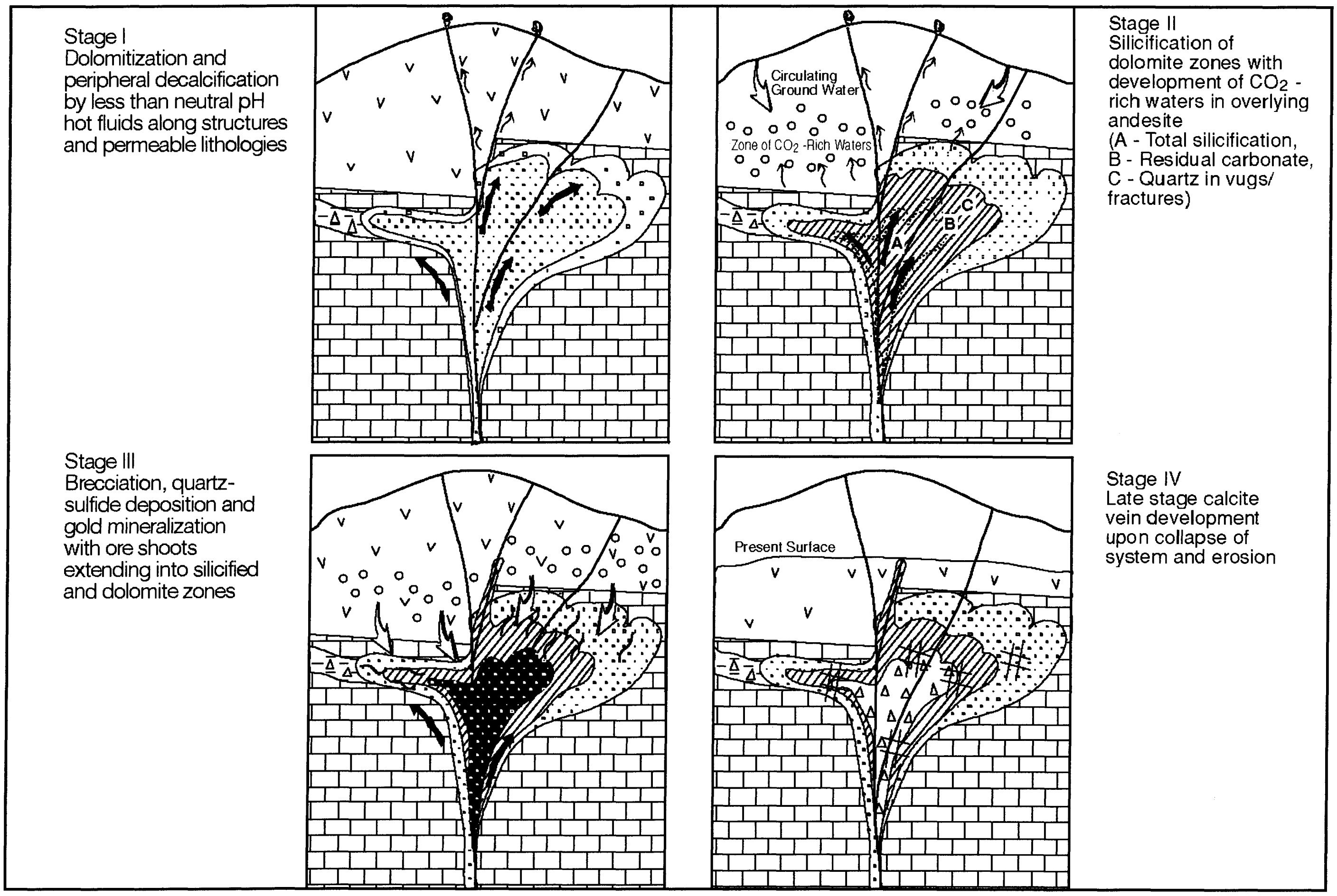

FIG. 7.58 Mesel — conceptual fluid flow model

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from decalcification and dolomitization as well as primary porosity in stylolitic fractures and sedimentary breccias. Silicification of dolomitized limestone proximal to the dilational structures created a brittle host rock, which fractured to form breccias containing quartz-pyrite-gold mineralization in the matrix.

It is proposed that dolomitization of the limestone and later silicification of the carbonates was caused by an influx of upwelling hydrothermal fluids of progressively decreased fluid pH, possibly due to an increasing gas content. Romberger (1988) proposed that simple cooling of an upwelling fluid would produce simultaneous dissolution of carbonate and precipitation of silica in Carlin-style sediment hosted replacement gold deposits.

Low pH fluids facilitate the precipitation of arsenic from near neutral hydrothermal fluids (Fournier 1985a). Arehart et al. (1993) illustrate that gold and arsenic are preferentially removed from solution by oxidation under moderately low pH conditions, and result in the coprecipitation of gold with arsenical pyrite or arsenopyrite. It is therefore interpreted that gold-bearing arsenical pyrite mineralization at Mesel developed in response to the mixing of upwelling mineralized fluids with low pH, CO_2-rich waters. The presence of zoned kaolinite-gypsum-smectite-illitic clays at shallow levels at Mesel, and of late kaolinite-pyrite in fractures, supports the model of CO_2-rich waters refluxing back into the hydrothermal system.