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Saddle Reef and Related Gold Mineralization, Hill End Gold Field, Australia: Evolution of an Auriferous Vein System during Progressive Deformation

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Abstract

Vein-type gold mineralization in the Hill End gold field, New South Wales, is hosted by a tightly to isoclinally folded succession of Silurian to Devonian turbidites. Scattered occurrences of anomalous gold mineralization are known in veins throughout the gold field, but economic concentrations of gold are generally restricted to the northern portion of the doubly plunging Hill End anticline. The Hill End anticline is the highest amplitude fold and has the structurally highest crest of folds in the region. Most of the economic gold occurs in bedding-parallel veins on the east-dipping limb of the anticline, but smaller rich deposits have also been mined from the west-dipping limb and from adjacent anticlines. Rich ore shoots in the bedding-parallel veins pitch subhorizontally and are associated with the intersections of these veins with narrow, subhorizontal, extensional veins, or leaders.

Vein textures indicate that both bedding-parallel and leader veins formed over a protracted interval, during regional deformation. Bedding-parallel veins started to form prior to folding and continued to form during regional deformation, acting as slip planes during late stages of flexural-slip folding. Leader veins formed as extensional fractures, due to transient supralithostatic fluid pressures developed in a low differential stress régime. Local zones of mineralized breccia and stockwork veining are also indicative of fluctuating fluid pressures and low differential stresses. During late stages of folding, as fold limbs attained steep dips, continued slip along them was permitted by transiently attained supralithostatic fluid pressures.

Gold mineralization occurred during the middle to latest stages of deformation. Mineralization was via low-salinity, H_2O-CO_2-CH_4 fluids. Gold deposition occurred in the vicinity of vein intersections as a result of repeated fluid pressure fluctuations that may have allowed mixing of relatively reduced fluids, which had locally equilibrated with carbonaceous wall rocks, with more oxidized, deeply sourced, auriferous fluids.

Introduction

THE Hill End gold field (production 56 t Au; Western Mining Corporation Staff, 1980, quoted by Seccombe and Hicks, 1989) is situated in central New South Wales, within the Paleozoic Lachlan fold belt, and in 1851 was the site of the first discovery of economic gold in Australia. It was known for its rich accumulations of very coarse gold, which occurred both as alluvial nuggets and as masses of gold and quartz in narrow quartz veins. The Hill End gold deposits occur on the flanks of the Hill End anticline and adjacent smaller anticlines, in a folded succession of Silurian to Devonian turbidites. They bear many similarities in terms of host rocks, structural style, and mineralization style to other Paleozoic turbidite-hosted gold deposits worldwide, including the Bendigo-Ballarat zone, central Victoria, Australia (e.g., Chace, 1949; Sandiford and Keays, 1986; Cox et al., 1987, 1991, 1995); the Meguma terrane, Nova Scotia, Canada (e.g., Graves and Zentilli, 1982; Mawer, 1986; Kontak et al., 1990); and the Welsh basin, U.K. (Fitches et al., 1986; Bottrell et al., 1988; Annels and Roberts, 1989).

The aims of this paper are (1) to document the structures, vein textures, and alteration mineralogy associated with the Hill End gold quartz mineralization, (2) to determine the relative timing of the veins with respect to regional deformation and granitoid intrusion, (3) to develop a genetic model for the Hill End gold mineralization, and (4) to discuss the similarities and differences of the Hill End deposits with other Paleozoic turbidite-hosted gold deposits.

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Regional Geology

The Hill End gold deposits are hosted by metamorphosed and deformed turbidites of the mid-Silurian to Early to Middle Devonian Hill End trough succession, part of the Paleozoic Lachlan fold belt (Packham, 1968). The edges of the Hill End trough succession are underlain by Ordovician to Middle Silurian metavolcanic rocks (Sofala Volcanics and Bell's Creek Volcanics; Packham, 1968; Scheibner, 1973). All of these rocks have been deformed into north-trending structures that are indicative of east-west shortening during regional deformation. Regional deformation, originally considered to have been a result of the Middle Devonian Tabberabberan orogeny (e.g., Packham, 1968, 1978), is now considered to be a result of the Lower Carboniferous Kanimblan orogeny (Cas et al., 1976; Crook and Powell, 1976; Powell, 1976, 1986; Powell et al., 1976; Powell and Edgecombe, 1978; Powell and Jones, 1978; Scott, 1991). The dominant structures in the Hill End area are regional-scale, gently doubly plunging folds which are tight to isoclinal in style, with an associated penetrative, axial planar, slaty cleavage, and steeply west-dipping reverse faults (Fig. 1). Minor late east-northeast-trending faults offset the main north-trending structures. Metamorphism is to chlorite and biotite grades of the greenschist facies, and peak metamorphism postdated cleavage formation (Vernon and Flood, 1979; Prendergast, 1981). Because primary sedimentary features are well preserved, in

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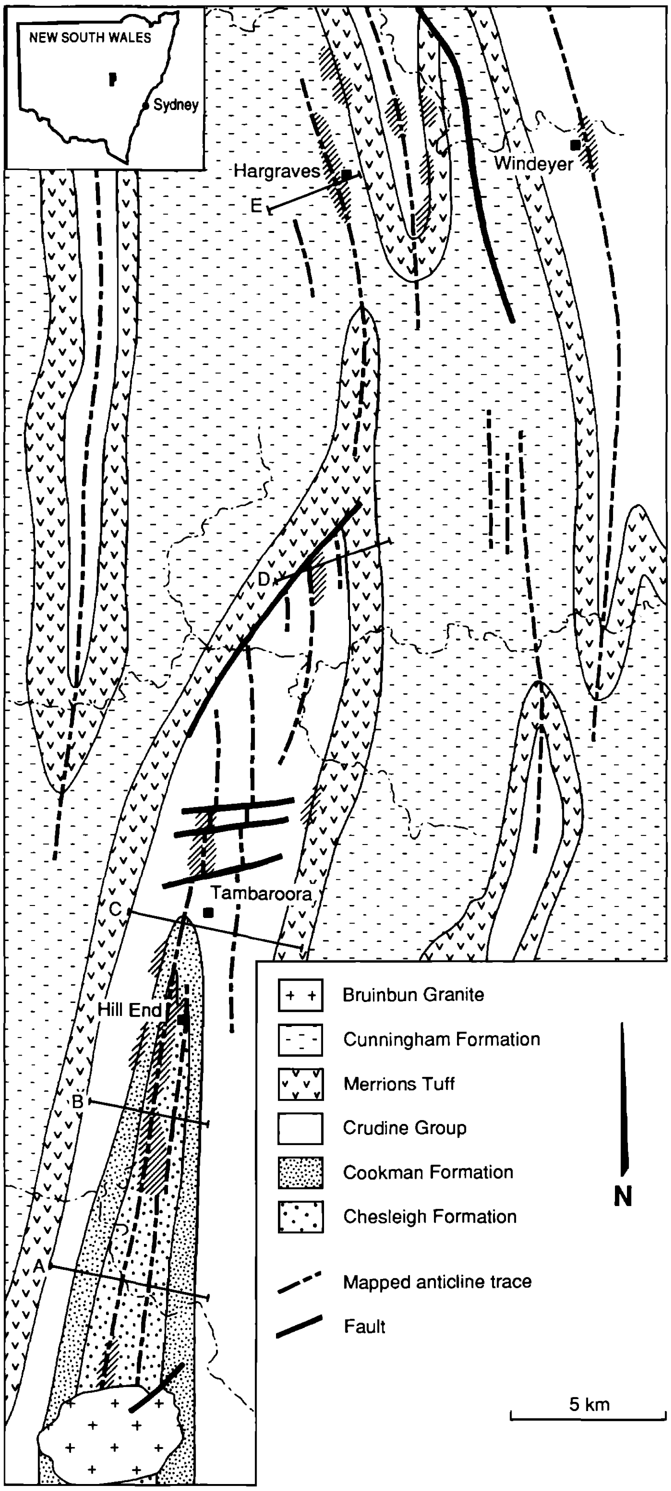

FIG. 1. Geology of the Hill End region and location of gold mineralization (diagonal hatch pattern). Locations of sections A–E, used to construct Figure 2, are shown.

this paper the prefix "meta-" is omitted and sedimentary rock names are used.

I-type granitoids of the upper Carboniferous Bathurst Suite crosscut the dominant structural trend and postdate the main regional deformation event (Cas et al., 1976; Bateman, 1979). The Bruinbun Granite, situated on the axial part of the Hill End anticline (Fig. 1), is part of the Bathurst Suite . It crosscuts structural trends, and mineralized veins hosted by the sedimentary rocks adjacent to it are contact metamorphosed. A single, narrow, undeformed lamprophyre dike exposed in the underground workings at Hill End has been emplaced parallel to cleavage and postdates the main deformational event. More detailed description of the regional geology is given by Packham (1968, 1978), Hobbs and Hopwood (1969), Packham and Conolly (1969), Scheibner (1973), Crook and Powell (1976), Powell (1976, 1986), Powell et al. (1976), and Powell and Jones (1978).

Geologic Setting of Mineralization

The geologic setting of mineralization in the Hill End region has been described by Watt (1898a, b), Harper (1918), Joplin (1949), Seccombe and Hicks (1989), and Windh (1990, 1991). Most of the economic gold occurrences in the Hill End region are located along the Hill End anticline (Fig. 1), which forms the structurally highest anticline and highest amplitude fold within a region of north-trending, tight to isoclinal folds. Smaller, minor gold deposits occur on adjacent anticlines, e.g., at Windeyer and at Tucker's Hill, between Windeyer and Hargraves (Fig. 1). The Hill End anticline is a doubly plunging anticline 80 km in length, which plunges northward in the area of Figure 1 and southward in the region south of Hill End. In the Hill End area, the regional Hill End anticline actually consists of two closely spaced anticlines separated by a syncline (Figs. 1 and 2). North of Hill End and Tambaroora, the regional-scale anticline is composed of smaller scale, right-stepping, en echelon anticlines and synclines (Fig. 1). The trend of these lower wavelength anticlines, discordant to bedding in the overlying Merrions tuff, is indicative of the presence of a west-dipping reverse fault separating the Merrions tuff from the underlying Crudine Group (Figs. 1 and 2). West-dipping reverse faults have been mapped northeast of Hargraves (Matson, 1973) and east of Hill End (Stevens, 1972). Crook and Powell (1976) predicted that blind thrust faults at depth should dip westward, and Glen (1992) interpreted a west-dipping blind thrust fault at the core of the Hill End anticline and a west-dipping emergent thrust adjacent to the anticline.

Fold style along the Hill End anticline is controlled by rheology and anisotropy of stratigraphic units (Fig. 2). Massive and competent units (Cookman Formation and Merrions tuff) are folded into a single, large anticline, whereas well-bedded (i.e., mechanically anisotropic) units are folded into numerous smaller scale folds. Well-bedded wacke-rich units (Chesleigh Formation, Crudine Group) are deformed into tight chevron folds and are thickened and locally faulted in the regional fold hinge, and bedded mudstone-dominated units (lower Cunningham Formation) consist of tight to isoclinal, similar-style folds.

Quartz vein-hosted gold deposits occur within the well-bedded units and are absent from massive units (Fig. 2). The Chesleigh Formation, exposed in the core of the Hill End anticline, hosts the gold mineralization at the town of Hill End and the smaller deposits on an adjacent anticline at Windeyer (Fig. 1). The gold deposits at Hargraves, 30 km

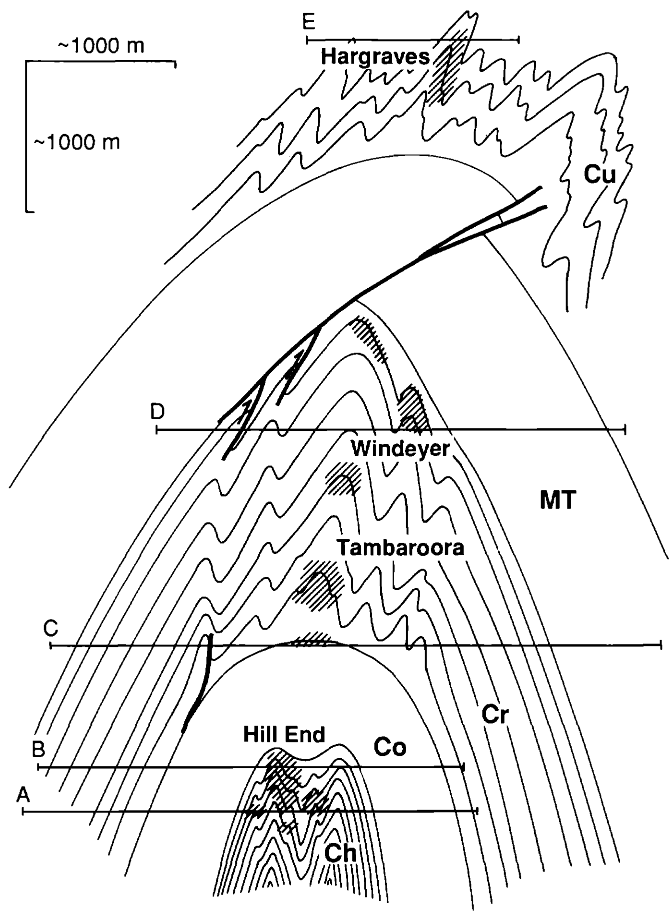

FIG. 2. Schematic composite section illustrating variable fold style on the Hill End anticline, controlled by relative rheology and degree of bedding-plane anisotropy of stratigraphic units. The stratigraphic position of the gold deposits is shown (diagonal hatch pattern), although some of the deposits, e.g., Windeyer, are actually hosted by smaller scale anticlines adjacent to the Hill End anticline. Sections A to E, used to construct this diagram, are located in Figure 1. MT = Marrions tuff.

north along the Hill End anticline, occur within the lower strata of the >3.5-km-thick Cunningham Formation, which consist dominantly of slate and minor thin feldspathic sandstone beds. Numerous small gold deposits occur within the Crudine Group, west and north of Hill End, and east of Hargraves.

The geometry of auriferous quartz veins is shown schematically in Figure 3. Economic gold mineralization occurs primarily within narrow, laminated, bedding-parallel veins. Veins thicken into saddle reefs at anticlinal crests, but they generally contain economic gold only on fold limbs adjacent to the saddles. Veins commonly contain economic gold mineralization on east-dipping fold limbs but are narrower and only rarely mineralized on west-dipping limbs. Historical records (e.g., Watt, 1898a, b; Harper, 1918) indicate that at least some of the rich ore shoots within the veins pitched shallowly to the north or south, and remaining underground exposures suggest that these shoots were associated with the intersection of the veins with narrow, shallowly dipping, crosscutting "leader" veins, which were so called because they "lead" the miners to the gold. Leader veins commonly contain visible gold but are too narrow to be of economic significance. A third, related style of mineralization that contains gold is brecciation and stockwork veining. Although only two examples of this type are known, they are economically significant for their potential to generate higher tonnages of ore than the narrow bedding-parallel veins. Unlike the rich gold fields of central Victoria (e.g., Cox et al., 1991), the anticlines hosting mineralization in the Hill End gold field are not breached by late reverse faults.

Vein Types

The geometry of the vein system, intensity of veining, and internal structures and textures of the veins provide constraints on the timing of vein formation and gold mineralization relative to regional deformation. These features also help to constrain the processes and dynamics of vein formation, including the regional stress régime, local and transient stress variations, and fluid pressures relative to lithostatic load.

Bedding-parallel veins

Bedding-parallel quartz veins have been the main gold-producing structures in the Hill End gold field. They are

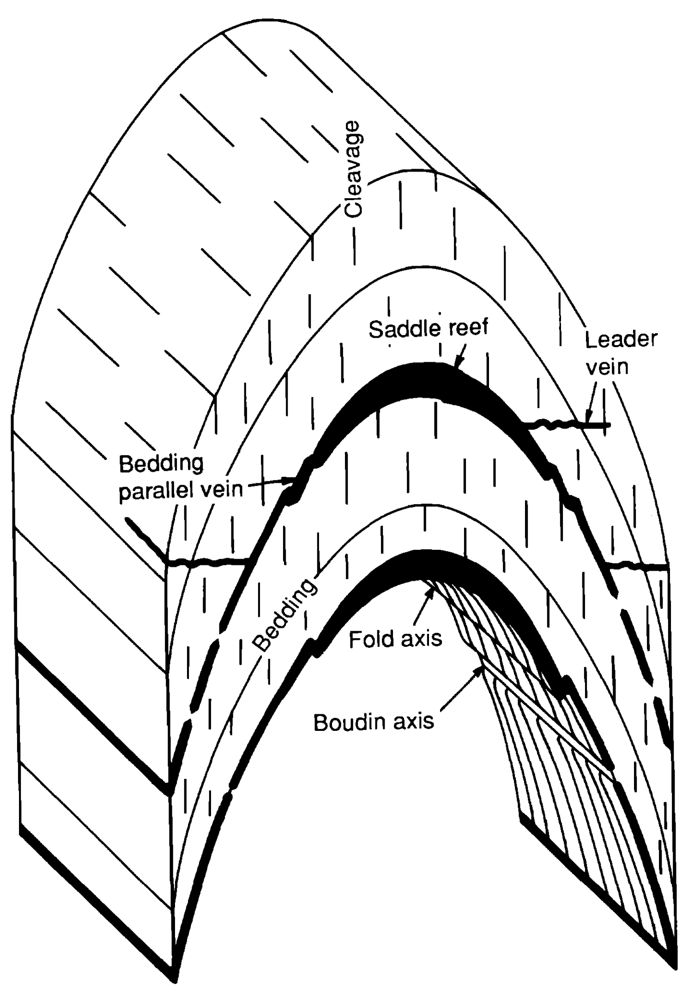

FIG. 3. Schematic block diagram showing geometry of veins relative to regional structures.

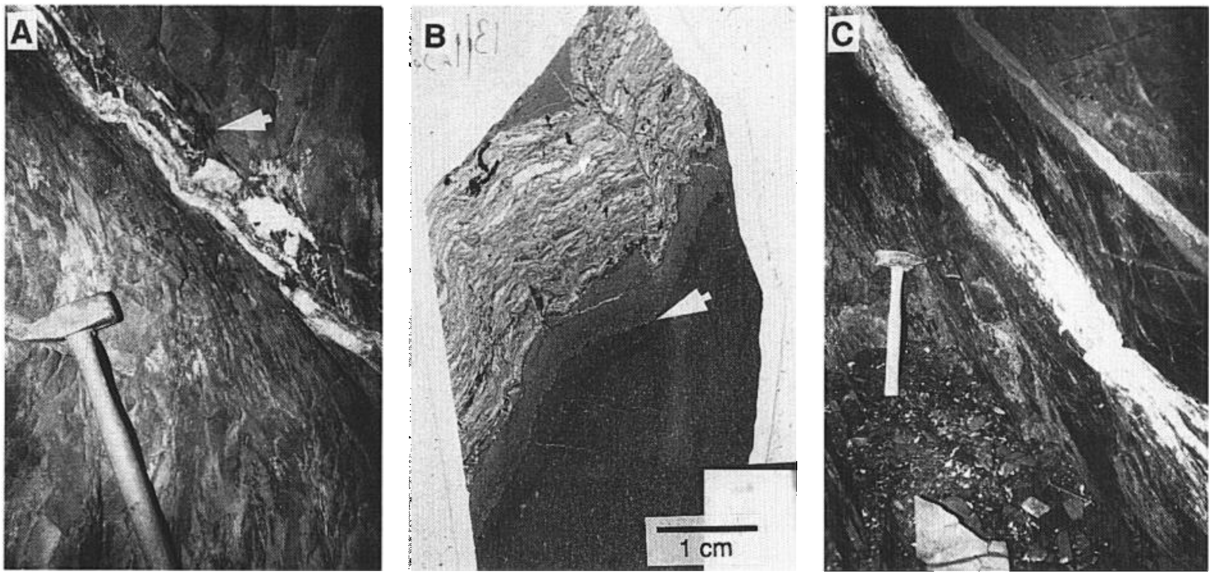

FIG. 4. A. Folded bedding-parallel vein hosted by Chesleigh Formation, Hill End. Vein occurs within thin mudstone capping a meter-thick graded wacke bed, several centimeters below the contact with the overlying wacke bed (arrow). B. Photomicrograph of bedding-parallel vein folded with bedding (arrow), hosted by Cunningham Formation mudstone, Hargraves. Vein occurs within a narrow graded feldspathic sandstone bed, millimeters above its contact with underlying mudstone. Plane-polarized light. C. Boudinaged bedding-parallel vein. Boudin axes are subparallel to regional fold axes.

relatively narrow (<1–15 cm) on fold limbs and up to 2 m thick on anticlinal crests. Vein quartz is laminated or composite laminated and massive. The veins are remarkably continuous and may follow a stratigraphic horizon for over a kilometer along strike and up to several hundred meters downdip. Historical records suggest that the veins thin and pinch out downdip. Present exposures, however, show that veins thin rapidly over several meters from fold crest, through the shoulder of the fold, to the top of the planar limb region, but that they remain relatively constant in thickness for hundreds of meters down the dip of the limb. Synclinal hinges are poorly exposed; in at least one example, however, a vein extending into a syncline remains constant in thickness, showing none of the thickening typical of the anticlinal saddle reefs.

The veins are located at two types of predictable bedding horizons, dependent upon the host lithology. They do not occur along lithological contacts but occur at specific horizons within certain beds, adjacent and parallel to lithological contacts. Which of the two predictable types of bedding horizons hosts the veins depends upon whether the local host stratigraphy is wacke dominated or mudstone dominated.

In the wacke-dominated Chesleigh Formation at Hill End and in the Crudine Group north of Hill End, the host rocks consist of meter-scale graded wacke beds capped by dark gray mudstones. The veins typically occur in the capping mudstones, 1 to 4 cm below the contact with the overlying graded wacke bed (Fig. 4A). The location of laminated bedding-parallel veins within mudstone beds, rather than along lithological contacts, is also recorded for the Meguma terrane (e.g., Graves and Zentilli, 1982; Henderson et al., 1990), in the Welsh basin (Fitches et al., 1986), and for at least some of the veins at Bendigo (e.g., Dunn, 1892, plates 10A, 13A, 14A).

The mudstone-dominated Cunningham Formation at Hargraves consists of thin (1–5 cm) graded feldspathic sandstone beds separated by several meters of featureless gray mudstone. Bedding-parallel veins here are typically developed within the sandstone beds, millimeters above their basal contacts with underlying mudstone (Fig. 4B). Where bedding-parallel veins are developed, these narrow sandstone beds are clearly favorable hosts for the veins. However, most such beds do not host bedding-parallel veins.

In all host-rock types, bedding-parallel veins consist dominantly of quartz, with subordinate calcite and chlorite. Accessory minerals include muscovite, minor (<1%) sulfides (pyrite, chalcopyrite, galena, sphalerite, and local pyrrhotite and arsenopyrite), and native gold. They are laminated or composite laminated and massive veins. Bedding-parallel veins thicken at fold crests to become saddle reefs, which consist of massive, vuggy quartz with few or no laminations. They are generally barren of gold mineralization and accessory minerals.

The vein laminations consist of chlorite and muscovite, with rare, narrow wall-rock inclusions, and contain striations oriented at high angles to regional fold axes. The striations are not quartz fibers; where fibers are preserved, they are oriented at a high angle to vein laminations and hence to their contained striations. Microscopically, the veins contain two scales of laminations: larger scale (120 μm–4 mm), narrow, planar phyllosilicate laminations which are gently inclined to the vein boundary; and smaller scale (10–150 μm) laminations which consist of crack-seal inclusion bands oriented parallel to the vein boundary, their topography mimicking wall-rock topography (Fig. 5A). The inclusion bands consist of screens of cleaved wall rock. Inclusion trails of carbonate grains are only rarely observed and are oriented parallel to the larger scale vein laminations (Fig. 5A). Quartz fibers, where preserved, are oriented at high angles to vein bound-

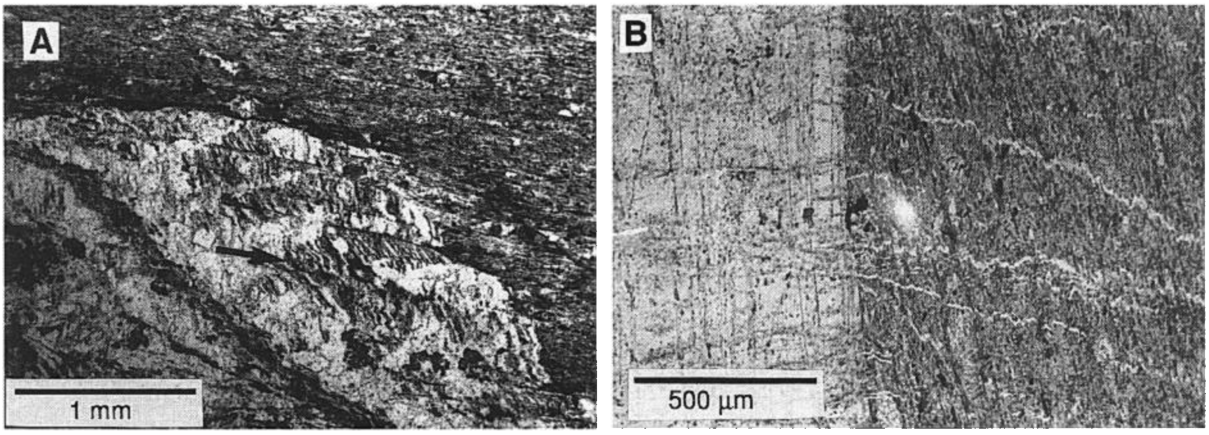

FIG. 5. A. Crack-seal laminations of cleaved wall rock in a bedding-parallel vein. Matched lamination topography and a crack-seal inclusion trail (arrow) indicate that the larger scale, very planar laminations are oriented parallel to the vein-opening direction. Plane-polarized light. B. Late subhorizontal quartz veinlets crosscutting a bedding-parallel vein. Veinlets are planar within the larger vein but are folded in the less-competent wall rocks. Cleavage in the wall rock is oriented at a low angle to the bedding-parallel vein and to bedding (bedding is not visible in photograph). Plane-polarized light.

aries and are oblique to both scales of vein laminations. Vein microstructures are similar to those described by Cox (1987) for veins from the Bendigo-Ballarat zone, central Victoria, and are indicative of a vein opening direction highly acute or nearly parallel to the vein margin, parallel to the trace of the continuous vein laminations (Fig. 5A). The veins therefore opened as bedding-parallel slip planes, with only a small component of opening perpendicular to the vein walls.

Most bedding-parallel veins are deformed. They are folded coaxially with the regional folds (Fig. 4A, B) and therefore started to form before, or during the early stages of, the regional folding. Laminations are commonly modified by pressure-solution processes into stylolite surfaces oriented parallel to vein walls. The veins are boudinaged, and the boudin axes are subparallel to regional fold axes (Fig. 4C). The quartz in the veins shows undulose extinction and is locally recrystallized, and veins are commonly cut by subhorizontal quartz veinlets that are planar within the veins but are folded where they extend into the adjacent wall rocks (Fig. 5B). These veinlets thus formed late in the deformation history, and after the bedding-parallel veins.

Leader veins

Leader veins are narrow (1–20 mm), subhorizontal to shallowly dipping, discordant veins that merge with, but do not crosscut, the bedding-parallel veins (Fig. 6A). They may be planar or folded, and where folded their enveloping surface is shallowly to moderately dipping. They are most abundant in the mudstone-dominated Cunningham Formation but are also common within the Chesleigh Formation. Their mineralogy is similar to that of the bedding-parallel veins, consisting dominantly of quartz, with lesser calcite and chlorite. Ore minerals include sulfides (pyrite, pyrrhotite, arsenopyrite, and rare sphalerite) and native gold, and they are more abundant, relative to vein width, in leader veins than in bedding-parallel veins.

Leader veins are crack-seal veins which crosscut cleavage (Fig. 6A–C); they are similar to veins described by Ramsay (1980) and Cox and Etheridge (1983). Crack-seal laminations are well developed near vein margins but are generally absent from the centers of the veins (Fig. 6B, C). The laminations consist of inclusion bands of oriented phyllosilicate grains and cleaved wall-rock fragments, and they are spaced 10 to 200 μm apart. Less deformed parts of the veins contain quartz fibers oriented perpendicular to vein margins, whereas quartz in folded parts of the leader veins has been recrystallized, developing a polygonal texture. The veins are moderately to highly deformed, some being shortened in excess of 60 percent by folding and pressure solution associated with the regional cleavage-forming event (Fig. 6B).

Brecciation and stockwork veining

Mineralized breccia occurs at the Frenchman's Reef, hosted by the Chesleigh Formation at Hill End. It consists of a bedding-parallel zone of economic gold mineralization up to 10 m wide, which was reputed to have been one of the most productive reefs of the gold field, although few records of its production exist. The breccia consists of randomly oriented fragments of cleaved, veined wall rock and laminated vein fragments in a matrix of quartz, calcite, and chlorite. Fragmented veins and veined wall rock, and numerous crosscutting veins, are indicative of repeated episodes of brecciation. Disseminated pyrite occurs both within wall-rock fragments and matrix.

Stockwork veining hosts vertically extensive low-grade gold mineralization in Cunningham Formation mudstones at the crest of the Hill End anticline, north of the town of Hargraves (Fig. 1). The veins are narrow (generally <1 cm), and although they crosscut cleavage, they have been weakly flattened and folded by deformation associated with further cleavage development.

Timing

Textures and structures described above are indicative of vein formation during all stages of regional deformation. Relative timing of regional structures and veins is summarized in Figure 7.

Bedding-parallel veins show textural evidence indicative of

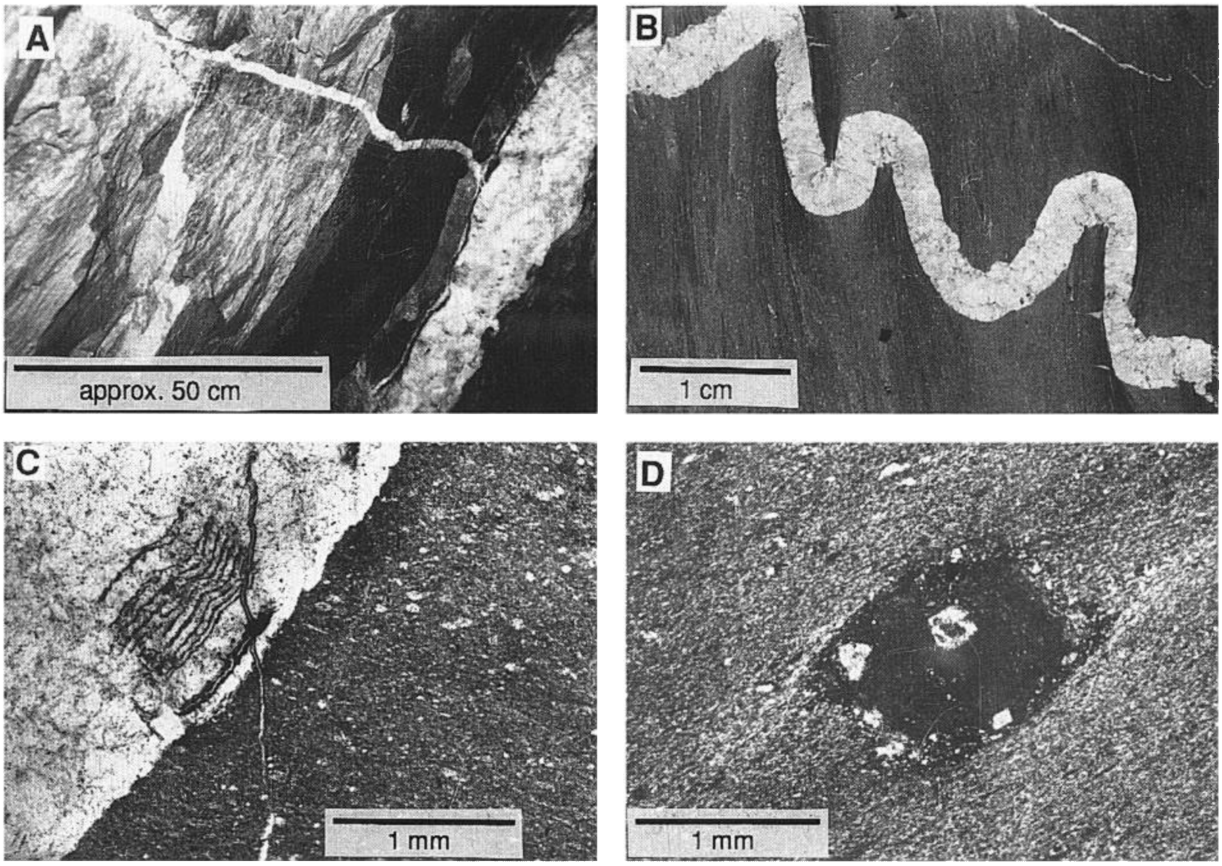

FIG. 6. A. Rich coarse-gold shoot in the Star of Hope vein, Hill End, located at the intersection of a narrow subhorizontal leader vein with a bedding-parallel vein. Both veins contain abundant visible gold. Width of field 1 m. B. Folded and pressure-solved leader vein, Cunningham Formation, Hargraves. The regional cleavage is axial planar to the folds. Plane-polarized light. C. Leader vein, showing discordant nature of leader vein to cleavage and crack-seal inclusion bands within the vein. The inclusion bands consist of screens of cleaved wall rock. Plane-polarized light. D. Carbonate porphyroblast with strain shadows showing weak asymmetry consistent with bedding-parallel shear during folding. Crossed polars.

their initiation prior to regional folding and of continuing vein development during regional folding. They thicken at anticlinal hinges and contain striations oriented approximately perpendicular to regional fold axes, both consistent with vein formation during flexural-slip folding. They also contain crack-seal inclusion bands of cleaved wall rock, indicative of vein formation during regional deformation. However, the

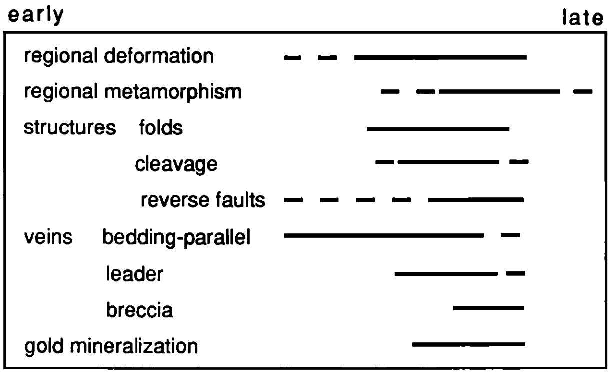

FIG. 7. Relative timing of regional structures, vein formation, and gold mineralization.

apparent continuity of at least some bedding-parallel veins around synclinal hinges and the occurrence of the veins within certain beds rather than along bedding contacts (i.e., potentially mechanically active surfaces during flexural slip folding) suggest that the veins may have started to form prior to folding (Windh and Zentilli, 1991; and discussion below).

Leader veins crosscut cleavage and contain crack-seal inclusion bands of cleaved wall rock, indicating that they formed after the onset of regional deformation and cleavage formation. However, they are deformed to varying degrees by the regional deformational event and hence at least had started to form before the end of deformation. The incorporation of cleaved and veined wall-rock fragments and laminated (bedding-parallel) vein fragments into the Frenchman's Reef breccia and the absence of any strong penetrative deformation of the breccia indicate that repeated brecciation events occurred during later phases of deformation. The weakly flattened stockwork veining at Hargraves is discordant to cleavage and thus formed late during regional deformation.

Hydrothermal Alteration

Hydrothermal alteration of wall rocks is minor. Limited white mica alteration of the wall rock occurs within millimeters of veins, and arsenopyrite occurs locally as disseminations of coarse-grained euhedral crystals adjacent to bedding-parallel veins at Hargraves. Carbonate (ankerite and/or calcite) porphyroblasts occur within tens of centimeters of some bedding-parallel veins and as broader halos at anticlinal fold hinges. Strain shadows and dissolution of the carbonate porphyroblasts (Fig. 6D) are consistent with carbonate deposition before the end of deformation. Strain shadows are symmetric to weakly asymmetric, and the asymmetries are consistent with bedding-parallel shear associated with flexural-slip and flexural-flow folding.

Gold Mineralization

Most of the economic gold mineralization in the Hill End gold field is hosted by east-dipping bedding-parallel veins adjacent to anticlinal hinges, with only minor mineralization occurring in west-dipping veins. However, many bedding-parallel veins contain little or no gold mineralization. This applies to certain veins in the main gold-producing areas at Hill End and Hargraves, many of the bedding-parallel veins on the west limb of the Hill End anticline, and numerous bedding-parallel veins in the strata between the Chesleigh Formation and the Cunningham Formation. Barren bedding-parallel veins are texturally identical to the auriferous veins, but they contain relatively more quartz and less chlorite and sulfide. There is a spatial association between the rich gold-bearing veins at Hargraves with local plunge reversals of the regional fold axis, but no such association is apparent in the main gold-producing area at Hill End.

Gold distribution within economic bedding-parallel veins forms rich shoots, at least some of which appear to have been shallowly plunging (e.g., Watt, 1898a, b; Harper, 1918) and associated with the intersection of leader veins. Examples of this relationship include the recently exposed Star of Hope vein in the Amalgamated adit at Hill End (Fig. 6A), and the Big Nugget vein in the Hill End shaft at Hargraves. Harper (1918) indicates that payable gold also occurred in wall rocks immediately adjacent to the bedding-parallel veins.

Gold occurs in several forms in the bedding-parallel veins. Primary native gold is enclosed by quartz, locally in contact with calcite or fine-grained galena; such gold is commonly confined to one or more laminations within a vein in the vicinity of its intersection with a leader vein (e.g., Star of Hope vein). Primary gold also occurs as very fine grains or thin films at the vein and wall-rock contact, (e.g., the Mica vein in the Amalgamated adit, Hill End), or along fine, irregular fractures that crosscut laminations in the bedding-parallel Big Nugget vein, Hargraves, near its intersection with a leader vein. Gold that is located along stylolitized laminations within the bedding-parallel veins has been either introduced, or locally remobilized, during the latest phases of fold tightening.

Native gold is common in the leader veins, generally occurring as discrete grains away from vein margins, surrounded by quartz or in contact with calcite or sulfides.

Very localized, rich, coarse gold accumulations (e.g., the 286-kg Holtermann gold and quartz "nugget") are associated with intersections of bedding-parallel veins with late, brittle, crosscutting faults. These subvertical faults, known locally as "cross courses," trend east-northeast, dextrally offset bedding-parallel veins by up to several decimeters, and postdate folding. Exposures of such mineralized intersections have long been mined out. Historical descriptions (Harper, 1918) indicate that they were commonly associated with quartz blows, which, in places consist almost entirely of white quartz, with occasional black bandings or irregular-shaped kernels; while in others, large and small angular fragments of slate occur, forming a regular breccia. In many cases these occurrences have been proved to contain high gold values, whilst others do not pay to work. Their origin is not quite clear, for whilst they almost invariably occur in the vicinity of faults, thus implying a connection between the two, in the observed cases the quartz appears to merge into the bedded veins, which have been displaced by the faulting, and consequently were of an earlier origin.

The displacement of these late faults is consistent with the east-west shortening operative during the main folding event. The faults may therefore have formed during the latest stages of the main deformation, after shortening by folding had ceased; alternatively, they may have formed significantly later than the regional folding. Historically rich deposits at Red Hill, north of Tambaroora (Fig. 1), are spatially associated with larger faults with orientations and apparent displacement directions similar to those of the cross courses at Hill End. No exposures of mineralized cross courses remain; mineralization associated with these faults may have been emplaced at the end of regional deformation or may represent supergene remobilization of gold by recent ground-water movements.

Ore Fluid Characteristics

Geochemical studies (Seccombe and Hicks, 1989) suggest peak metamorphic conditions of 420°C and 2.9 kbars, based upon the calcite, ferroan-magnesian calcite geothermometer and the Si content of white mica, respectively. Fluid inclusion work on both bedding-parallel veins and leader veins shows a protracted history of quartz deposition and indicates that gold was deposited from low-salinity (0.1–3.6 wt % NaCl equiv), H_2O-CO_2-CH_4 fluids that evolved to progressively more oxidized compositions with time (Lu and Seccombe, 1992). Homogenization temperatures of inclusions associated with gold mineralization range from 190° to 260°C (Lu and Seccombe, 1992), and inclusions generally homogenize to the liquid phase and only rarely homogenize to the vapor phase (P.K. Seccombe, writ. commun., 1992). The temperature data are consistent with vein development during greenschist facies metamorphism.

Isotopic compositions of sulfur for seven samples of pyrite and sphalerite from mineralized veins range in $\delta^{34}S$ values from −2.8 to 17.8 per mil, with five of these samples lying within the range of 5.3 to 7.5 per mil (Seccombe and Hicks, 1989). This wide range of values is not consistent with a direct magmatic contribution of sulfur to the hydrothermal system, and it suggests that the sulfur may have been derived from sedimentary, and possibly volcanic, rocks underlying the present gold deposits during metamorphism and deformation (Seccombe and Hicks, 1989).

Constraints on a Genetic Model

Constraints on a genetic model for the Hill End gold deposits are imposed by: (1) regional structural style and location of gold deposits relative to regional structures, (2) litho-

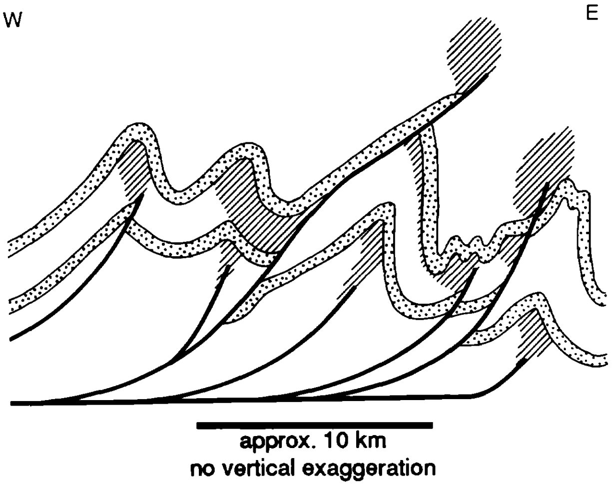

FIG. 8. Semischematic regional cross section of probable deep fault structure responsible for folding and focusing of fluid flow from a laterally displaced source area. West-dipping reverse faults die upward into anticlines and channel rising fluids preferentially into east-dipping fold limbs (areas of diagonal hatch pattern).

logical characteristics of the host rocks, (3) vein siting, geometry, and timing relative to regional deformation and the process of vein formation as indicated by vein textures, (4) location of gold deposits within the vein system, and (5) geochemical constraints on the composition and source of ore fluids and controls on gold deposition. The critical relationships are discussed below.

Regional structures

Regional folds, faults, and cleavage development are all indicative of east-west shortening and vertical extension during regional deformation. Reverse faults, both mapped (Stevens, 1972; Matson, 1973; this study) and interpreted or inferred from regional studies (Crook and Powell, 1976; Glen, 1992), dip consistently westward. The major gold deposits are situated along the Hill End anticline, the structurally highest anticline in the region. The veins that host economic mineralization are bedding parallel, but are wider and more richly mineralized on the east-dipping limb of the anticline. These features together suggest that net fluid transport was upward and focused along lithological anisotropies such as bedding, that mineralization must have occurred late relative to folding, and that there was an asymmetric, or lateral, component to the net upward fluid flow in order to account for richer mineralization in east-dipping fold limbs. West-dipping reverse faults at depth, which die in displacement upward, could account for the introduction of ore fluids preferentially into east-dipping fold limbs. Such a large-scale blind fault, situated below and to the east of the Hill End anticline, might account for both the anticline itself, with displacement on the fault transferring into fold development updip, as well as for the rich gold mineralization concentrated primarily along its east-dipping limb for over 40 km of strike length (Fig. 8). A blind thrust fault that cores the Hill End anticline has also been inferred by Glen (1992).

Host rocks

The veins and gold deposits are not confined to one particular stratigraphic formation or lithotype. For example, the two richest gold deposits, Hill End and Hargraves, whereas structurally and mineralogically similar, are hosted by the wacke-rich Chesleigh Formation and mudstone-rich Cunningham Formation, respectively. The deposits are, however, confined to rock units with specific attributes, i.e., they are well bedded on the scale of centimeters to meters and contain beds of highly variable composition. These characteristics indicate that the key control on bedding-parallel vein formation is not a specific rock type or association but rather the juxtaposition of beds of strongly anisotropic physical parameters, e.g., ductility, cohesion, permeability.

Vein siting and geometry

The siting of the laminated veins within certain beds, the geometry of the vein system, and vein textures all constrain the timing of vein formation relative to regional deformation and the processes involved in vein formation. The siting of the veins within selected beds, rather than along bedding contacts, is particularly important in understanding the early history of vein formation. If vein formation had occurred during flexural-slip folding, the veins would be predicted to occur along bedding contacts; this is not the case at Hill End. Flexural flow of the less competent mudstone was likely a more important deformational mechanism at Hill End, and it is suggested by locally divergent cleavage fanning in the mudstones and by asymmetric fabrics about carbonate porphyroblasts in the cleaved mudstones (e.g., Fig. 6D). However, deformation by flexural flow cannot alone account for the development of discrete fractures or veins within the mudstone horizons or for the preferred siting of veins in narrow sandstone beds in the Cunningham Formation.

The occurrence of veins within beds, rather than on bedding contacts, suggests that the physical property responsible for localizing veins to certain beds was not relative ductility but another parameter such as permeability or tensile strength (refer to discussion below). Folding and boudinage of some of the veins indicate that they formed relatively early in the deformation history, and the continuity of veins around synclinal troughs suggests that they may predate much or all of the folding. These veins thus record an early bedding-parallel slip event. The orientation of the vein striations, subperpendicular to the regional fold axes, is suggestive of a kinematic relationship between this early bedding-parallel slip event and regional folding. The bedding-parallel slip (and possible associated minor thrust ramps) may thus represent the earliest increments of the east-west shortening event that ultimately resulted in the regional folding.

Timing of vein formation

The Hill End bedding-parallel veins are interpreted to have started to form prior to regional folding. Similar laminated and striated bedding-parallel veins in Nova Scotia and Wales have been interpreted to have formed prior to folding, as subhorizontal hydraulic fractures formed either during dewatering of the sedimentary pile or during regional metamorphism (Graves and Zentilli, 1982; Fitches et al., 1986; Henderson et al., 1990). Critical evidence for an early origin for these veins includes, in Nova Scotia, euhedral vein quartz crystals which penetrate into the adjacent wall rock, interpreted as indicating that the wall rocks were unlithified when the vein formed (Henderson et al., 1990), and in Wales, the presence of laminated and striated bedding-parallel veins even in unfolded parts of the basin (Fitches et al., 1986). The similarities between these vein systems and the Hill End veins are suggestive of a common mode of formation for all of these bedding-parallel veins.

A common feature of the Hill End veins and the early formed Nova Scotian and Welsh veins, as well as at least some of the bedding-parallel veins from Bendigo, Victoria, Australia, is the siting of bedding-parallel veins in wacke-dominated host successions within mudstone beds rather than along lithological contacts (Nova Scotia: Graves and Zentilli, 1982; Henderson et al., 1990; Welsh basin: Fitches et al., 1986; Bendigo: Dunn, 1892, plates 10A, 13A, 14A). These mudstone beds, whether lithified or not, would be less permeable than the adjacent wackes (Fig. 9A) and would tend to develop higher pore fluid pressures during dewatering and metamorphism. A scenario including high pore fluid pressures, a horizontal maximum compressive stress (as suggested by the regional fold geometry), and a possible horizontal mechanical anisotropy due to compaction of the mudstones, would promote bedding-parallel failure and subsequent slip within the mudstone units (Fig. 9A). In the case of the mudstone-dominated succession at Hargraves, permeabilities would be low and pore fluid pressures would be high throughout the unit. The thin sandstone beds would be less permeable and would localize fluid flow; with a horizontal maximum compressive stress, the lower tensile strength of the sandstone relative to the surrounding mudstones might promote bedding-parallel failure within the narrow sandstone beds (Fig. 9B).

The evidence outlined above argues for a prefolding timing for initiation of the laminated bedding-parallel quartz veins. However, vein textures indicate that the veins were modified and that significant amounts of additional quartz vein material was added, particularly at anticlinal hinges, to form saddle reefs during bedding-parallel slip associated with regional deformation (Fig. 9C, D). Although the timing of some crack-seal laminations is equivocal, some of the crack-seal laminations are clearly associated with bedding-parallel slip during folding and postdate most cleavage development. Vein textures indicate that leader veins formed over a protracted interval; they started to form after the onset of cleavage development and probably continued to form throughout the folding episode (Fig. 9C, D). Their subhorizontal attitude and crack-seal textures indicate that they represent extensional fractures formed by transiently attained supralithostatic fluid pressures in a régime with a subvertical minimum principal stress, compatible with the stress field inferred for the regional deformation event, and low differential stresses (e.g., Etheridge, 1983; Etheridge et al., 1983, 1984; Cox et al., 1987). The Frenchman's Reef breccia, and the stockwork veining at Hargraves, are also indicative of cyclical fluid pressure fluctuations and low differential stresses.

Siting of gold

Gold occurs in trace amounts in most veins in the Hill End region. Economic concentrations, however, occur only within a few vein sets, and rich gold shoots are confined to specific structural sites within veins. On the larger scale, the occurrence of gold in only some of the bedding-parallel vein sets probably relates to regional fluid flow patterns. Where no discordant faults exist, fluids follow anisotropies such as bedding and cleavage and are focused toward anticlinal hinges and local domes. The occurrence of all the major gold deposits on the structurally highest anticline in the region, in particular near the domal crest of the anticline at Hill End, and their association with a plunge reversal at Hargraves supports general upward fluid migration focused along bedding. Broad halos of carbonate alteration around anticlinal fold hinges are suggestive of dispersed upward fluid flow above saddle reefs (as discussed by Cox et al., 1991, for the Bendigo gold field).

On a smaller scale, rich gold shoots within auriferous veins are subhorizontal and associated with intersecting discordant leader veins that are themselves richly mineralized. Leader veins are indicative of at least transiently attained supralithostatic fluid pressures. As folding progressed and bedding-parallel veins, which behaved as small reverse faults during flexural slip folding, rotated to progressively steeper dips, the normal stress across them increased and they became less favorably oriented for reverse slip. Once bedding dips exceeded about 55°, slip associated with folding could only occur if pore fluid pressures were in excess of lithostatic load (e.g., Sibson, 1990a, b). Thus, by later stages of folding, bedding-parallel veins and leader veins could have formed a linked system of veins activated by cyclical fluid pressure fluctuations, analogous to the reverse fault-flat vein system at Sigma mine described by Sibson et al. (1988). The veins formed by a repeating cycle of fluid pressure buildup, resulting in opening of the extensional veins, followed by a fault rupture episode causing an instantaneous fluid pressure drop, rapid upward fluid migration, and subsequent fault sealing and repetition of the cycle (Sibson et al., 1988). At Hill End, the association of gold shoots with the vein intersections suggests that gold deposition was a consequence of these fluid pressure cycling events.

Gold occurs in folded leader veins and along quartz laminations in bedding-parallel veins, indicating that it was deposited synchronous with vein deposition, during the middle stages of regional deformation. The location of gold along fractures discordant to laminations in bedding-parallel veins indicates that gold deposition continued after much of the vein formation, during the later stages of regional deformation. There is no evidence of gold mobilization during the earliest stages of bedding-parallel vein formation. Although veining commenced prior to regional folding and continued throughout all stages of deformation, significant gold transport and deposition occurred only during the middle to latest phases of deformation (Fig. 7).

Fluid constraints

Fluid inclusion data (Lu and Seccombe, 1992) indicate that the vein minerals were deposited from low-salinity, H_2O-CO_2-CH_4 fluids. The ore fluid composition is typical of fluids derived from low-grade metamorphism of sedimentary and volcanic rocks. Homogenization of most inclusions to the liquid phase and the H_2O-rich nature of the inclusions militate against phase separation as the main control on gold deposi-

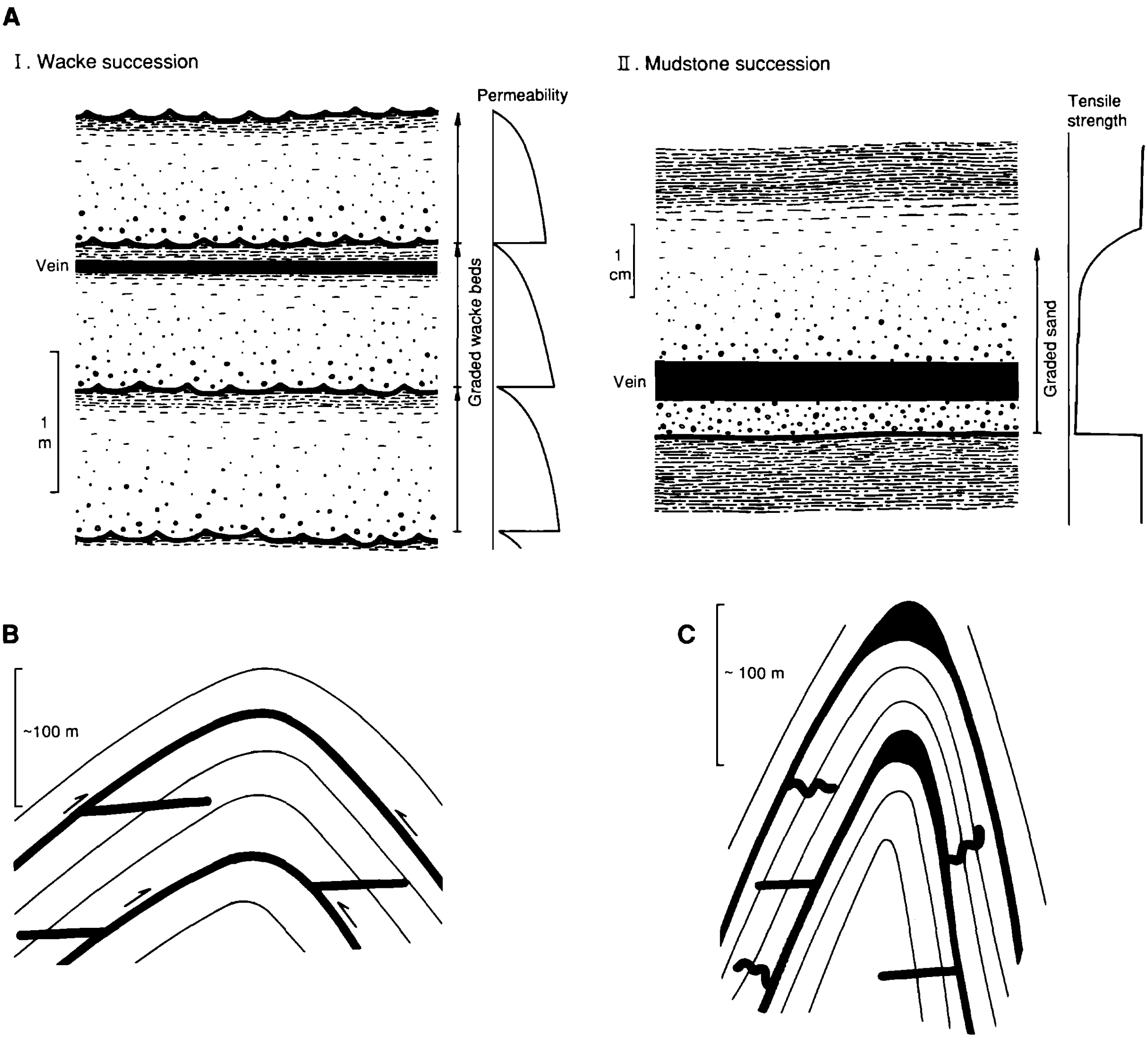

FIG. 9. Model for formation of the Hill End vein system. A. Veins form parallel to bedding during compaction due to local supralithostatic fluid pressures developed during dewatering and/ or metamorphism. Veins form within relatively impermeable mud beds in wacke-rich succession (I) and in narrow, low-cohesion sand beds in mudstone-rich successions (II). B. Slip along bedding and continued vein formation occur during folding and horizontal extensional fractures (leader veins) form. C. Continued deformation results in folding of bedding-parallel veins and dilation at fold hinges, folding of older leader veins, and continuing formation of new leader veins.

tion, and they suggest that deposition may have been a result of either fluid mixing or wall-rock reaction. Sulfur isotope data (Seccombe and Hicks, 1989) eliminate a direct magmatic contribution to the ore fluids and suggest that at least some of the ore fluid components were derived from the underlying sedimentary, and possibly older volcanic, rocks. All of these features are consistent with conclusions drawn from structural studies: that much of the quartz veining and gold mineralization occurred during regional deformation and lower greenschist facies metamorphism and prior to granitoid emplacement.

Summary and Discussion

Bedding-parallel veins started to form prior to regional folding and possibly prior to lithification of their host sediments. They record early bedding-parallel slip that may have been associated with the compressional stress régime that was ultimately responsible for regional folding. The veins were modified, and further vein material was added, during regional flexural slip folding. As deformation progressed, transiently attained supralithostatic fluid pressures formed subhorizontal, extensional leader veins and local zones of brecciation and stockwork veining. By the later stages of folding, when fold limb dips exceeded 55°, bedding-parallel veins dipped too steeply to permit continued reverse movement, and further folding by flexural slip was maintained by the development of supralithostatic fluid pressures which counteracted high normal stresses across the veins. Rich gold accumulations occur along the intersections of bedding-parallel veins with discordant leader veins, which were sites of cyclical fluid pressure fluctuations. Fluid pressure fluctuations may promote gold deposition by either causing phase separation of the ore fluid, and subsequent destabilization of gold bisulfide complexes (e.g., Phillips, 1972; Naden and Shepherd, 1989), or by allowing local mixing of fluids in equilibrium with wall rocks with more deeply sourced ore fluids (Cox et al., 1991). Fluid inclusion studies show no evidence supportive of phase separation but are permissive of local fluid mixing. Similar gold deposits in the Bendigo-Ballarat zone also occur along structural intersections, which were sites of repeated fluid pressure fluctuations, and gold deposition there is interpreted to have resulted from mixing of fluids that had locally equilibrated with carbonaceous wall rocks by infiltration along discordant fractures with more deeply derived, relatively oxidized, auriferous fluids ascending along bedding-parallel fault veins, as a result of these fluid pressure fluctuations (Cox et al., 1991).

The regional siting of the gold deposits provides constraints on regional-scale fluid flow patterns during regional deformation. The location of all major deposits on a regional anticline supports net upward fluid flow. However, the general occurrence of rich mineralization on east-dipping fold limbs, and the inferred presence of west-dipping reverse fault(s) coring the anticline, suggests that there was a lateral component to fluid flow and that ore fluids were derived from the west (Fig. 8). Similarly, ore fluids responsible for mineralization within the Bendigo-Ballarat zone are also considered to have been derived from a laterally displaced (westerly) source (Cox et al., 1991).

The Hill End gold field bears numerous geologic similarities to other Paleozoic turbidite-hosted gold deposits, particularly in the Bendigo-Ballarat zone, the Meguma terrane, and the Welsh basin. The Welsh basin hosts bedding-parallel veins that bear textural similarities to the Hill End veins (Fitches et al., 1986); gold mineralization is hosted by both bedding-parallel and discordant fault veins (Bottrell et al., 1988; Annels and Roberts, 1989). Intensity of deformation in the Meguma terrane, Nova Scotia (e.g., Mawer, 1986), is broadly similar to that at Hill End, with regional folds and rare, large-scale reverse faults accounting for the major structures and gold mineralization hosted by bedding-parallel veins on and near anticlinal hinges. Deformation in the Bendigo-Ballarat zone has progressed further than at Hill End, with the development of ubiquitous, small-scale, reverse faults that breach anticlinal hinges and appear to have developed as accomodation structures during the latest stages of regional deformation (e.g., Cox et al., 1991). These late faults, and associated veins, host rich gold mineralization associated with saddle reef veins in the Bendigo-Ballarat zone (Cox et al., 1991, and references therein).

All of these Paleozoic turbidite-hosted gold systems bear numerous similarities, and it is likely that they formed by broadly similar mechanisms, with differences between them largely reflecting differences in the geometry of the smaller scale structures; i.e., leader veins at Hill End, and the breaching reverse faults at Bendigo-Ballarat. General processes, including deformation mechanisms, timing of various vein types relative to regional deformation, and ore fluid characteristics, are similar. The total gold production from each of these regions varies, from the Welsh basin (about several metric tons Au), to the Meguma terrane (approx 60 t Au) and Hill End gold field (56 t Au), to the highly productive Bendigo-Ballarat zone (approx 750 t Au). One factor that might promote rich gold mineralization is the development of discordant veins, e.g., the Hill End leader veins and the Bendigo-Ballarat breaching faults. The intersections of discordant veins with the bedding-parallel veins would be sites of repeated fluid pressure fluctuations that promoted gold deposition. Fluid pressure fluctuations, developed particularly around structural intersections, e.g., of bedding-parallel veins with discordant veins or faults, may have caused gold deposition by allowing mixing of relatively reduced fluids, in equilibrium with carbonaceous wall rocks, with more oxidized ore fluids.

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