TURBIDITE-HOSTED GOLD DEPOSITS

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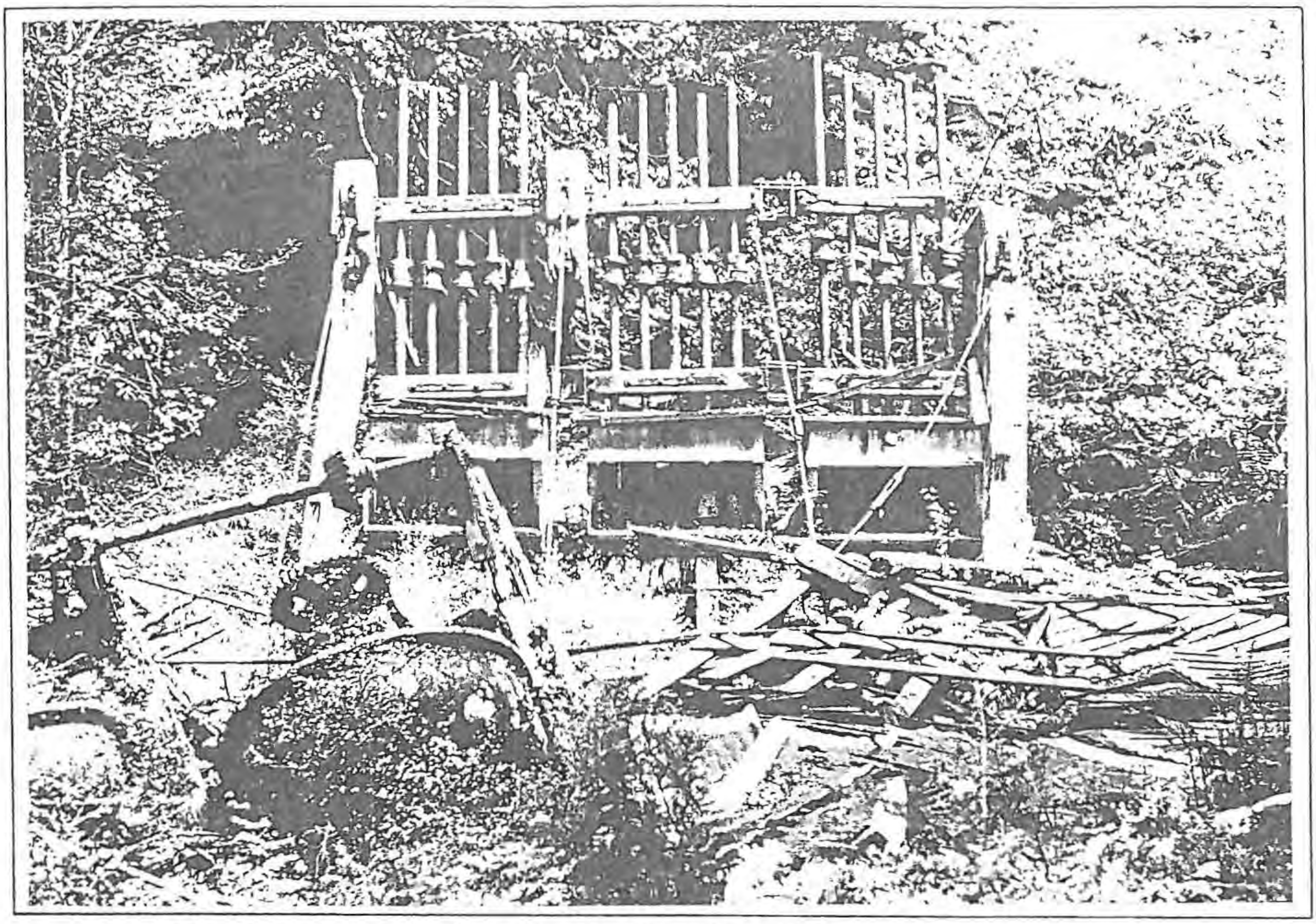

FRONTISPIECE: BATTERY STAMP OF THE REEFTON GOLDFIELD, NEW ZEALAND
(Courtesy photograph of P.N. Bentley)

> "I had long come to the conclusion that most if not all the gold in the quartz reefs was derived from the rock in which these reefs occur. That the strata themselves received their supply of gold at the period of their deposition from the ocean in which they were deposited. That the organic matter and the gases generated there from on decomposition, sulphuretted hydrogen etc. were the cause of the precipitation; and that the amount of metallic deposit was in proportion to the amount of organic matter deposited with the organic sediment"

R. Daintree, 1866 - Geology of the Ballan District, Victoria

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ABSTRACT

Turbidite-hosted gold deposits contribute a significant proportion to world lode gold production and have also provided substantial gold to alluvial resources. Turbidity current deposits occur throughout geological time within Archaean greenstone belts, Proterozoic orogenic belts and rifted passive continental margins, and Palaeozoic geosynclines. Representing the end member of the sedimentary cycle, turbidites have the attribute of preservation not only on an individual bed basis but also due to below wave base accumulation in submarine deeps. Cyclic deposition according to the Bouma sequence punctuates turbidite deposition by a series of diastems. Accumulation of organic, pelagic and chemical sediments may concentrate gold to protore enrichment levels in a primary sedimentary environment. Dewatering during diagenesis and low-grade metamorphism under reducing conditions may redistribute gold with transport as low energy organo- and thio-complexes. Gold may precipitate with diagenetic pyrite and silica near black shale and/or partially replace fine carbonate detritus.

Gold solubility increases with high grade amphibolite facies metamorphism (T 400°C) when efficient leaching of gold and transport by simple chloro- and hydroxychloro-complexes to lower greenschist regions takes place. Reduced permeability of turbidite strata induces hydrofracturing which focuses dewatering solutions. Gold is deposited due to pressure and temperature decrease or local changes in physico-chemico conditions caused by the reaction of fluids with wall rocks (reactive beds in turbidites are predominantly carbonaceous strata).

The largest of turbidite-hosted goldfields are confined to back-arc or marginal sea basins with restricted oceanic circulation. The richest concentrations of gold occur proximal to the original source within the greenschist facies formations lowermost in a thick turbidite sequence and exhibit strong combined structural and lithological association. Turbidites represent important strata for the concentration and preservation of gold not only during sedimentation and diagenesis but also during later deformation and metamorphism.

1. INTRODUCTION

The aim of this dissertation is to analyse the sedimentary environment and post-depositional history of turbidites in relation to gold mineralization. The importance of gold production from turbidite-hosted gold deposits will be briefly examined in relation to other gold producers.

The problems with classification of gold deposits will be discussed briefly to emphasize and attempt to define those geological features which are regarded as critical for flexibility in a working hypothetical exploration model.

The present status of the turbidity current theory will be reviewed with particular emphasis on the mechanics of deposition, the sedimentological features of turbidites and associated facies, and the environments of deposition on a regional and plate tectonic scale.

Gold mineralization in turbidites is almost exclusively hosted in quartz veins. Despite early lateral secretion ideas, magmatic hydrothermalists of the 1940's and 1950's particularly underplayed the role of the original host rock environment because of the epigenetic nature of quartz vein ores. In this dissertation it is proposed to examine carefully the geotectonic setting, sedimentary environment, co-magmatism (if any), and post-depositional history of turbidite-hosted gold deposits. Diagenesis, structural modification and metamorphism during continental accretion or orogeny form a significant part of the scenario and will be critically reviewed within the constraints of the presently known geochemical behaviour of gold. A number of appropriate case studies will be drawn upon but where possible, emphasis will be placed on the largest of gold producers.

Selection of this dissertation topic rests largely on the inspiration of personal observations at the Proterozoic Telfer gold deposit in the Paterson Province and a number of prospect areas in the Archaean Pilbara Block, Proterozoic Halls Creek Mobile Belt, and Bangemall Basin of Western Australia. Other turbidite-hosted gold prospects of Palaeozoic age were personally inspected in the Ballarat-Bendigo area of Victoria and in the Hodgkinson basin of north Queensland. In southern Africa gold deposits hosted in the Archaean Fig Tree Group of the Barberton Mountain Land were also inspected briefly this year.

Little research specifically devoted to this dissertation topic is presently available, although a number of workers have expressed interest in directing future research efforts into this type of mineralization (pers. comm. Button, Keays, Morrisson, 1984). Lack of present literature on turbidite-hosted gold deposits may be attributed to the redundancy of many goldfields over the past thirty years and the inaccessibility of present producers (e.g. Ashanti of Ghana, Murunteau of the U.S.S.R.). I wish to remind the reader of this poor documentation should parts of the dissertation appear speculative or inconclusive.

Reef-hosted gold is reputably erratic and represents a poor bulk mining proposition. It is hoped that this dissertation will conclude with a more positive genetic model for directing future gold exploration.

2. GOLD DEPOSITS : BOYLE'S CLASSIFICATION AND METAMORPHOGENIC ORE PROCESSES

Turbidite-hosted gold deposits are not a recognized class of gold deposit but maybe regarded as subdivisions within a classification such as that proposed by Boyle, (1979) (Refer categories 4 and 6.C.a. Table 2.1). Based on the geological and geochemical setting of gold, Boyle's classification (1979) is valuable in the sense that it immediately describes the type of ore deposit one might expect in a particular geological setting.

Table 2.1 Classification of Gold Deposits (Boyle, 1979, 1984)

1. Auriferous pegmatites, coarse-grained granite bodies, porphyry dykes and sills.
   e.g. * pegmatites in Madagascar.

2. Auriferous skarn-type deposits.
   e.g. + Nickel Plate, French Mines, British Columbia.

3. Gold-silver and silver-gold veins, stockworks, lodes mineralized pipes and irregular silicified bodies in fractures, faults, shear-zones, sheeted zones, and breccia zones essentially in volcanic terranes.
   e.g.s. Archaean greenstone belts, Mother Lode of California, Waihi of New Zealand, Emperor of Fiji.

4. Auriferous veins, lodes, sheeted zones and saddle reefs in faults, fractures, bedding-plane discontinuities and shears, drag folds, crushed zones and openings on anticlines essentially in sedimentary terranes; also replacement tabular and irregular bodies developed near faults and fractures in chemically favourable beds.
   e.g.s. Ballarat-Bendigo of Victoria, Reefton in New Zealand, Telfer of Western Australia, Pilgrims Rest in South Africa, Muruntau of the U.S.S.R., Caribou of Novia Scotia.

5. Gold-silver and silver-gold veins, stockworks and silicified zones in a complex geological environment comprising sediments, volcanics and igneous or granitized rocks.
   e.g.s. Kirkland Lake of Canada, Central City District of Colorado.

6. Disseminated and stockwork gold-silver deposits in igneous, volcanic and sedimentary rocks.
   A. Disseminated and stockwork gold-silver deposits in pyritized and silicified igneous intrusive bodies.
      e.g.s. + Bougainville in New Guinea; Morning Star mine of Woods Point, Victoria.
   B. Disseminated gold-silver and silver-gold occurrences in volcanic flows and associated volcanoclastic rocks.
      e.g.s. * Coromandel Peninsular of New Zealand, western U.S.A.
   C. Disseminated gold-silver deposits in volcanoclastic and sedimentary deposits:
      a) deposits in tuffaceous rocks and iron formations (refer chapter 5a and Eriksson, 1983)
         e.g.s. Madsen Mine at Red Lake Ontario; Archaean banded iron formations of greenstone belts in Canada, Australia, Zimbabwe, South Africa, Brazil and India; Homestake of Dakota.
      b) deposits in chemically favourable sedimentary beds
         e.g. Carlin, Cortez and Gold Acres of Nevada.

Table 2.1 Classification of Gold Deposits (Boyle, 1979, 1984) (cont.)

7. Gold deposits in quartz-pebble conglomerates and quartzites.
   e.g. Witwatersrand, Tarkwa of Ghana.

8. Placers
   - A. Eluvial including those developed in karst terranes
     e.g.s. Rio Tinto of the Pyrite Belt, Spain; Greenhorn of California.
   - B. Alluvial
     e.g. Otago goldfields, New Zealand; Palmer River, North Queensland.
   - C. Fossil eluvial and alluvial
     e.g. Deep leads of the Ballarat district, Victoria

9. +Miscellaneous sources including nickel-copper sulphides in mafic intrusives, polymetallic massive sulphide deposits, polymetallic vein and lode deposits and porphyry Cu-Mo type deposits.

* Gold resource is mostly subeconomic
\+ By-product gold is important.

Sediment-hosted gold deposits represent by far the most important class of gold producer in the world. Turbidite-hosted gold deposits contribute a significant proportion of today's gold production and rank with some of the highest producers in the world, after the Witwatersrand (Table 2.2).

Table 2.2: Ranking of individual gold mines according to their production in 1978. Host rock lithology is presented in brackets (Pretorius, 1981)

		Metric tons
1.	Muruntau, U.S.S.R (turbidites)	80,0
*2-12	Witwatersrand gold mines, South Africa (quartz pebble conglomerates)	447,9
+13	Bougainville, P.N.G. (porphyry Cu)	23,4
14	Western Areas Wits., South Africa, (quartz pebble conglomerates)	
26	Ashanti, Ghana (turbidites)	11,3
27	Pueblo Viejo, Domin. R. (acid volcanics, cherts, siltstones)	10,9
29	Homestake, U.S.A. (banded iron formation)	9,5
+33	Kennecott, U.S.A. (porphyry Cu-Mo)	6,3
34	Carlin, U.S.A. (carbonate)	5,7
+35	Philex, Phillipines (porphyry Cu)	6,1
37	Campbell Red Lake, Canada (acid volcanics)	
40	Telfer, Australia (turbidites)	4,7
47	Morro Velho, Brazil (banded iron formation)	3,5

* Individual gold mines have produced between 67,4 and 26,6 tons of gold
\+ Gold is produced as a by-product.

Geological Environment or Process of Ore Formation

Boyle's classification emphasizes the geological association of a gold deposit instead of the origins of ore formation which are often poorly understood. Notwithstanding, ore formation processes are important to understand within a given environment, but classification by process may be misleading.

For discussion purposes, supposing turbidite-hosted gold deposits are classified as a hydrothermal ore deposit. According to Henley (1973a) a hydrothermal ore deposit represents "an anomalously high concentration of metals restricted to very small volumes of the earth's crust and derived from the passage of hot aqueous solutions" or an aqueous solution of unspecified origin at elevated temperatures. Taylor (1979) differentiates a number of aqueous solutions applicable to hydrothermal ore deposits including meteoric, oceanic, geothermal, connate, metamorphic and magmatic. He concluded that many hydrothermal ore deposits defy simple classification because ore-forming solutions may overlap in isotopic composition.

Classifying gold deposits according to specific processes of ore formation is fundamentally erroneous if the definition of ore genesis is accepted as the combination or sum of physical and chemical processes which concentrate metals (Henley, 1973a). Recognition of multi-stage ore genesis and the dynamics of each relevant ore forming process must be regarded as the principle objective of any exploration geologist. In this way the tendency to overlook subtle features within an environment of ore deposition will be avoided.

Any ore deposit including gold requires a penultimate source of metal. The source of gold only becomes less mysterious when all facets and possibilities of gold behaviour in a geological environment are considered. Ultimately the frustrated research scientist may invoke heterogeneities in the upper mantle e.g. by associating all Archaean gold with sulphur-undersaturated komatiites in greenstone belts (Keays, 1984) or specific mantle behaviour during crustal evolution to characterize particular metallogenic periods (Watson, 1973; Pretorius, 1976; Woodall, 1979) (Figs. 2.1, 2.2).

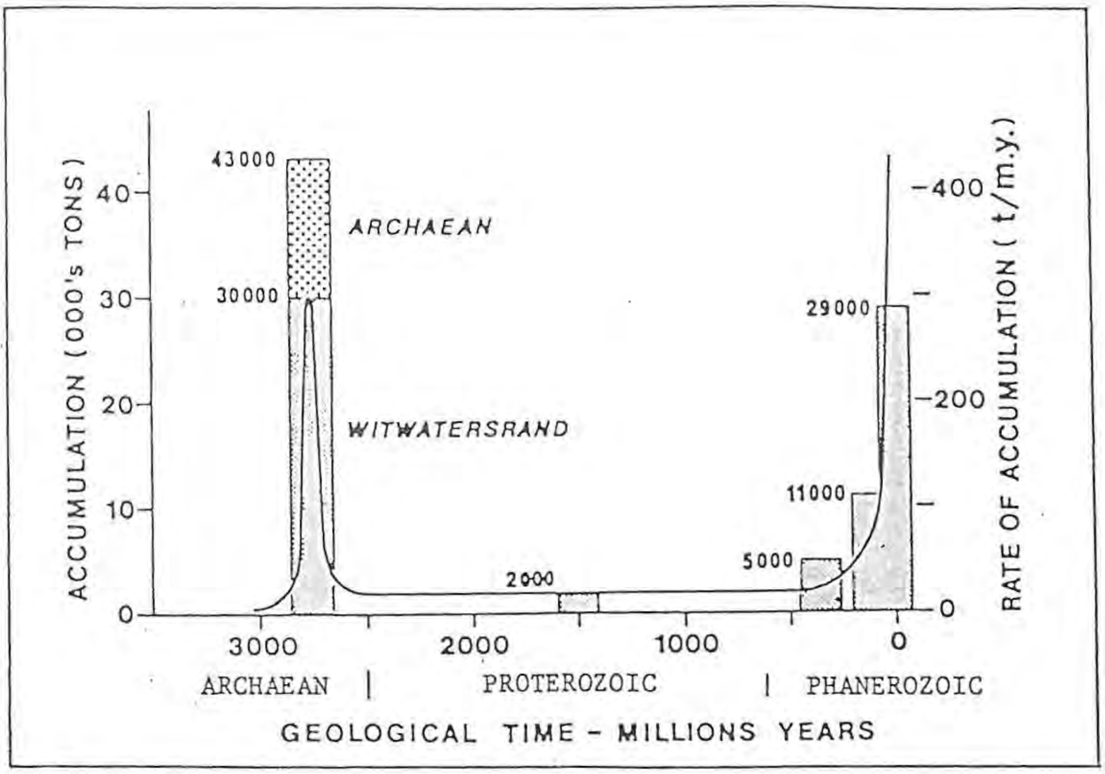


Figure 2.1 Gold in geolgical time (Woodall, 1979)

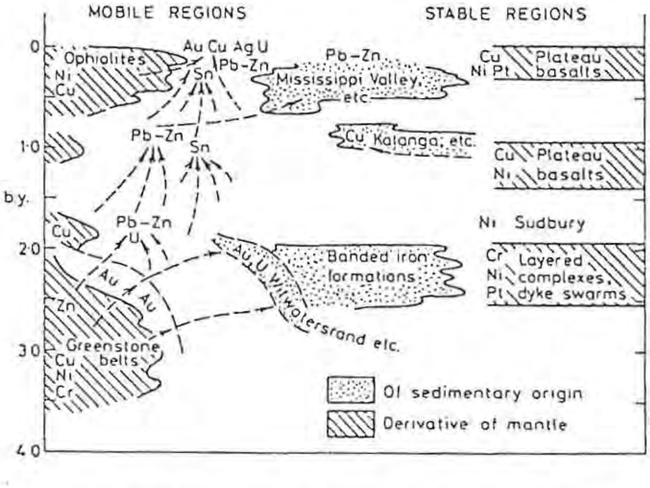


Figure 2.2 Summary diagram illustrating possible relationships of ore deposits formed during successive stages of crustal history (Watson, 1973)

2.1 Towards a Better Model

Shortsightedness in considering a number of processes with respect to ore genesis leads to obsession with relating mineralization to background levels of metal abundance in a particular rock type.

This is particularly true with respect to auriferous vein deposits in sedimentary rocks. Basin-wide metamorphism is often held responsible for the hydrothermal source of metal-bearing solutions which concentrate gold into specific structural settings to form ore deposits. Dewatering due to metamorphism is particularly effective for leaching background levels of gold from huge thicknesses of sediments, and channelling metal-laden solutions into favourable chemical and/or structural traps where gold is eventually deposited. It is doubtful whether such solutions fractionate to produce gold-enriched fluids as the metamorphic model suggests, because testing of such models often falls short (Henley et al, 1976; Glasson and Keays, 1978). In much the same way earlier models for vein-gold attributed auriferous quartz-vein systems to igneous intrusion and extreme magmatic fractionation; vein material and gold were introduced into the host rock environment, which simply provided the framework for the migration and precipitation of ore-bearing fluids. The shortcomings of magmatic models lie in the inability of magmas to fractionate gold and the fact that ore precipitation is largely controlled by the depositional environment.

Lateral secretion advocates acknowledged that the original sedimentary environment was gold-enriched and that post-depositional processes only served to modify and in many cases up-grade a protore enrichment to ore grade levels. No one, as far as the author has found, has investigated in detail why turbiditic environments may significantly concentrate gold. By the very nature of the process, sediments are eroded, transported and rearranged from one place (the source) to another (the sediment). A gold provenance in turbidites may simply represent the product of a removed gold provenance from elsewhere. Early lateral secretion models favoured for gold mineralization in sediments were invariably rejected because hosting sediments were no longer anomalous in gold.

The turbidite environment, including associated magmatism during sedimentation may represent a period when initial preconcentration of gold on a protore basis is significant. However, metamorphic dewatering of turbidite sequences most certainly assumes genetic importance for the final enrichment and present dispostion of most orebodies in turbidites. Deformation and metamorphism may also be solely responsible for protore enrichment in turbidite terranes which for example, form source terranes for extensive alluvial gold deposits. The relative genetic importance of protore enrichment and metamorphic dewatering may vary for any goldfield and must be assessed in accordance with geological observation.

Uniformitarian concepts permit the study of the present as a key to the past. Excellent research into the dynamics of sedimentation accompanying alluvial, fluvial and eluvial processes responsible for concentrating both recent and ancient placer gold deposits is available (Pretorius, 1974, 1976; Minter, 1978). Study of modern geothermal systems in regions of active or recently active volcanism has elucidated aspects of many Tertiary hydrothermal ore deposits (Henley and Ellis, 1983) which have readily found applicability in the geological time record (De Wit, 1982; Rossiter, 1984). Knowledge of the geochemical behaviour of gold in specific environments has also reached sophisticated levels (Boyle, 1979; Seward, 1984; Fyfe and Kerrich, 1984 and Roedder, 1984).

By closely reviewing the dynamics, environment, and post-depositional history of turbidite formation and appropriately predicting the geochemical behaviour of gold for each stage, it is hoped that a more definitive model for ore formation in turbidites may be erected. The following chapter will firstly review the principle features and terminology of the turbidity current theory.

3. TURBIDITES, FLYSCH

a. Definitions

A turbidite is defined as "the deposit of a turbidity current", which is itself defined as a "density current in which the difference in density between the current and ambient fluid (commonly sea water) is due to the presence of dispersed sediment". There is no connotation of scale of flow, or depth of ambient fluid implied by this definition (Walker and Mutti, 1973). The only depth connotation of turbidites is that a turbidity current deposits its sediment below the storm wave base (commonly only tens of meters) ensuring preservation of its turbidite characteristics.

A turbidite basin, in which thick accumulations of turbidites may take place without significant reworking by tidal, storm, long-shore or semi-permanent ocean currents include deep lakes, cratonic or fjord basins, block faulted continental border lands, elongate exogeosynclinal troughs and major ocean basins (Nelson and Kulm, 1973; Walker and Mutti, 1973). General principles of turbidite deposition apply equally to large and small scale systems. Depths of the former reach hundreds or thousands of metres and the influence of reworking is minimal. Contour currents may rework very fine sediments on some continental rises and these deposits are referred to as contourites.

Flysch as defined by Mitchell and Reading (1978) represents "any thick succession of alternations of sandstone, calcarenite or conglomerate with shale or mudstone interpreted as having been deposited by turbidity currents or mass flow in a deep water environment within a geosynclinal belt". The term "flysch" is preferably avoided for turbidites or turbidite-like beds in fluvial, lacustrine or deltaic environments. "Sediment gravity flow" or "mass flow" is a general term used to describe the flow of sediment or sediment-fluid mixtures under the action of gravity (Middleton and Hampton, 1973).

b. Types and Mechanics of Mass Flow

Processes involved with subaqueous mass gravity flow, with which turbidites are primarily associated include in order of increasing internal disaggregation:-

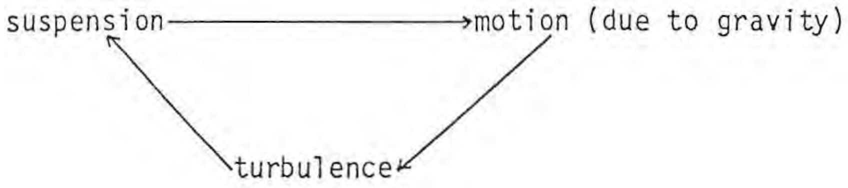
1) rock fall

2) sliding and slumping, and
3) sediment gravity flow (Fig. 3.1).

Sediment gravity flows are classified according to grain support mechanisms and include debris flow, grain flow, fluidized sediment flow and turbidity flow deposits (Fig. 3.2, Middleton and Hampton, 1973). Mechanisms include suspension (by turbulence), saltation (by hydraulic forces and drag) and traction (by dragging and rolling particles on the bottom). Distinct types of flow are likely to occur together and produce or modify some of the structures and textures in the final deposit. An important point to note is that subaqueous mass-gravity transport is a resedimentation process (Rupke, 1978).

Turbidity currents appear to be surges, which are initiated by some event (more or less catastrophic) and move downslope from the source (Fig. 3.3). Surges are subdivided into head, body and tail, within which respective hydraulics are described in Figure 3.4. The entrained layer, a zone of mixing between the body of the current and water above, may continue to flow after the body of current has passed, and hence rework the upper part of the sediment deposited by the body and tail.

Turbulence generated at the boundaries of the flow represents the main sediment supporting mechanism. Before flow of a turbidity current takes place, an initial input of energy is required to create a suspension. Once flow begins, it may continue indefinitely provided the energy loss due to friction is replaced by the input of gravitational energy (Middleton and Hampton, 1973). That is, in the hypothetical state of "autosuspension":-



Sediment slope failure is caused by either an increase or a decrease in shear strength (Fig. 3.5). Increasing shear strength results by steepening of the slope caused by

1) wave undercutting, current action or slope failure further down slope, and

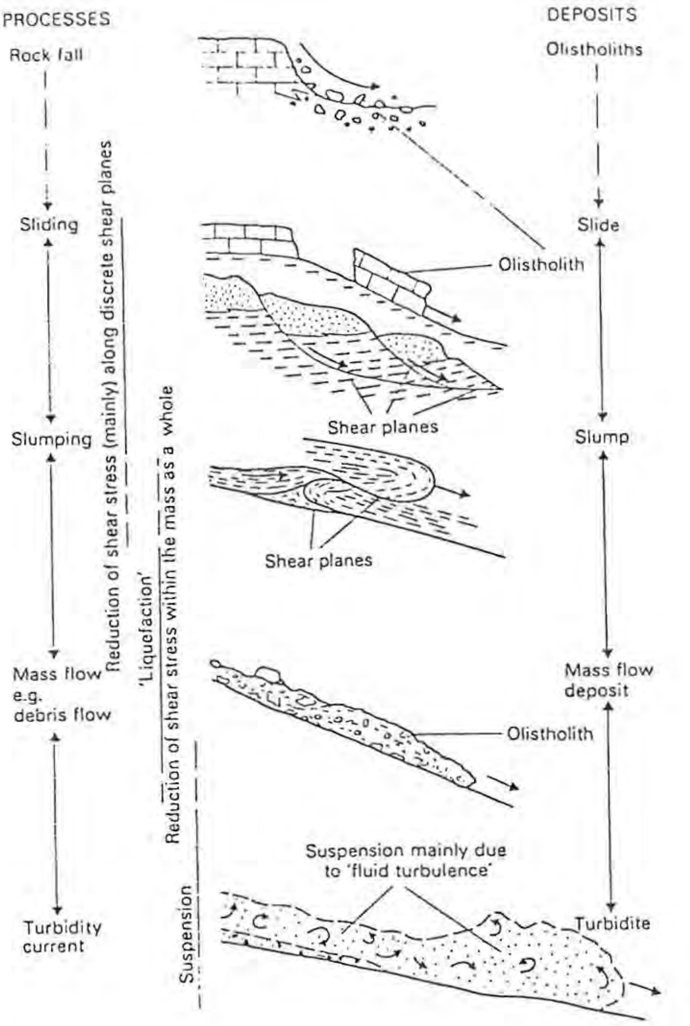


Figure 3.1 Processes of mass-gravity transport and their deposits (Rupke, 1978)

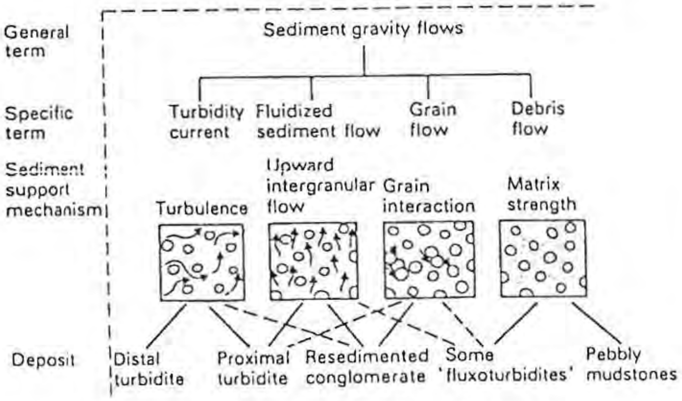


Figure 3.2 Classification of sediment gravity flows based on the mechanism of grain support (Middleton and Hampton, 1973)

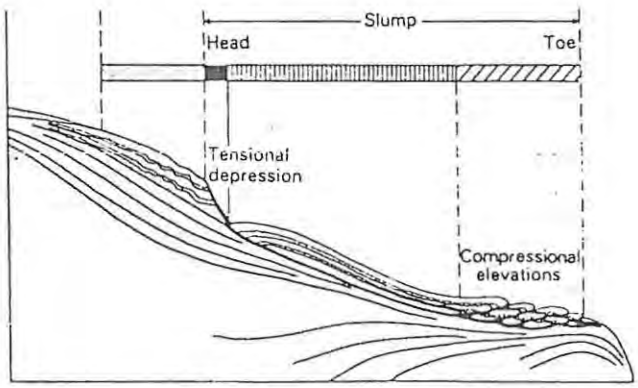
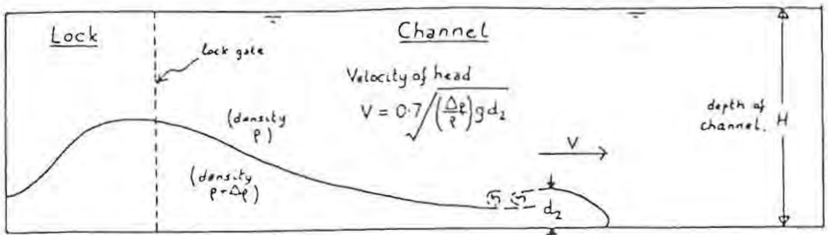
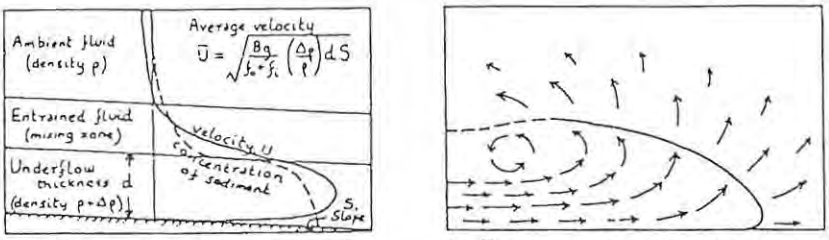


Figure 3.3 Diagrammatic cross-section of a submarine slump on a gentle slope (from Lewis, 1971) (Rupke, 1978)



A. Turbidity Current Surge



B. Steady Uniform Flow

C. Flow in and around the Head

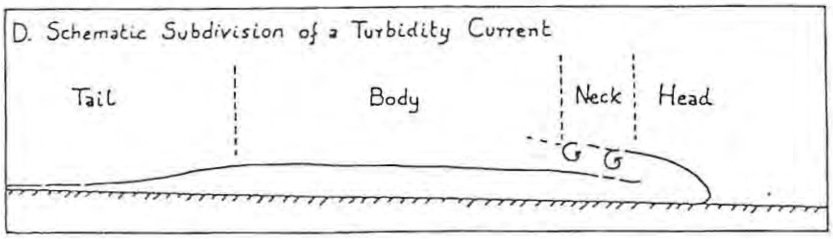


Figure 3.4 Hydraulics of turbidity currents. A. Turbidity current surge, as observed in a horizontal channel after releasing suspension from a lock at one end. The velocity of the head, v, is related to the thickness of the head, d_2, the density difference between the turbidity current and the water above, p, the density of the water, p, and the acceleration due to gravity, g. B. Steady, uniform flow of a turbidity current down a slope, s. The average velocity of flow, u, is related to the thickness of the flow, d, the density difference, and the frictional resistance at the bottom (f_0) and upper interface (f_i). C. Flow pattern within and around the head of a turbidity current, D. Schematic division of a turbidity current into head, neck, body and tail (Middleton and Hampton, 1973)

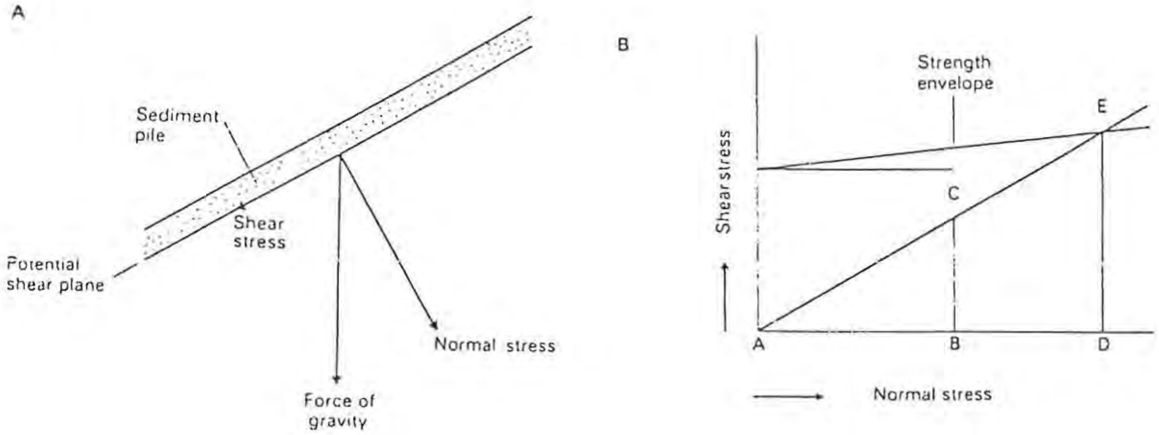


Figure 3.5 A. Vector diagram of the weight of a sediment pile on a slope. B. Graphic presentation of the shear strength of a sediment (after Moore, 1961) (Rupke, 1978)

2) thickening of the sediment pile by deposition.

Decreasing shear strength is caused by

1) increase in fluid pressure leading to sediment fludization, and
2) thixotropic behaviour in which gel-sol transition takes place.

Fluidization and thixotropy tend to be induced by mechanical impact or shock such as earthquakes, tsunami waves, storms and turbidity currents (Rupke, 1978).

In reality, not all parts of the turbidity current surge in a state of autosuspension so that while erosion occurs at the head, deposition takes place from the tail or the rear of the head. Rapid deposition occurs in proximal regions due to decay of intense turbulence, rapid flattening of slope and overbank flow.

c. Facies and Facies Associations

Five main facies are recognized in an environment characterized by sediment gravity flow: classic turbidites, massive sandstones, pebbly sandstones, conglomerates and debris flows (Fig. 3.6). Massive sandstones are thick, coarse and commonly channellized deposits. They lack the sedimentary structures of turbidites but do show evidence of dewatering (dish structures). Pebbly sandstones are poorly graded but may contain parallel stratification and large-scale cross-stratification. Conglomerates of debris flows are characterized by parallel and cross-stratification and commonly show a preferred clastic fabric (imbrication) (Walker, 1978). They are massive, and both poorly sorted and graded deposits. Sedimentary structures of these facies are briefly summarized in Figure 3.7.

Classic turbidites are distinguished from the other facies by:

1) parallel bedding with consistent alternations of sandstone and shale (normally without channelling); and
2) a consistent set of internal sedimentary structures that may be described using the Bouma model.

Turbidites are "classic" in the sense that such beds have received extensive study since the concept of turbidites and turbidity currents was first introduced by Kuenan and Migliorini (1950) (Middleton and Hampton, 1973; Walker, 1978). These concepts were then used to explain cable breaks and sand layers in the Atlantic ocean (Heezen and Ewing, 1952).

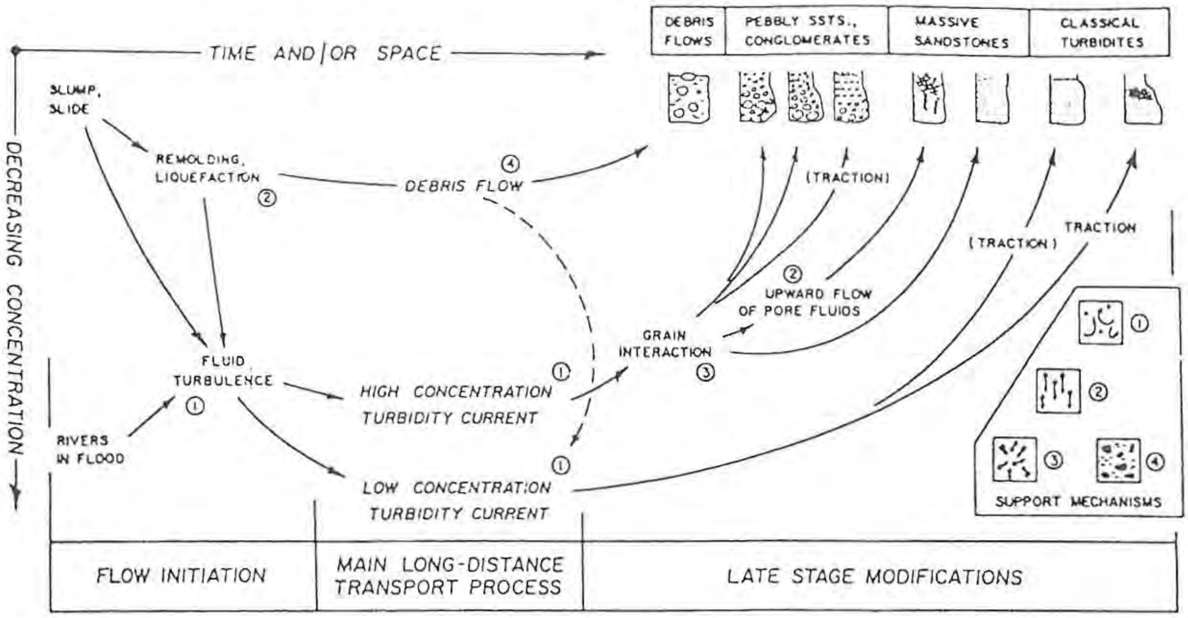


Figure 3.6 Processes of initiation, long-distance transport, and deposition for currents transporting sediment into deep water. Framework is one of time and/or space, and concentration of flows. Grain-supporting mechanisms (insert, lower right) include: 1, fluid turbulence; 2, liquefaction; 3, collision between individual grains (dispersive pressure in grain flow); and 4, matrix strength (as in debris flow). Modified in discussion with Middleton (personal comm.) from Middleton and Hampton (1976), to show possibility of debris flows becoming turbulent, and to eliminate grain flows as long-distance transport processes (Walker, 1978)

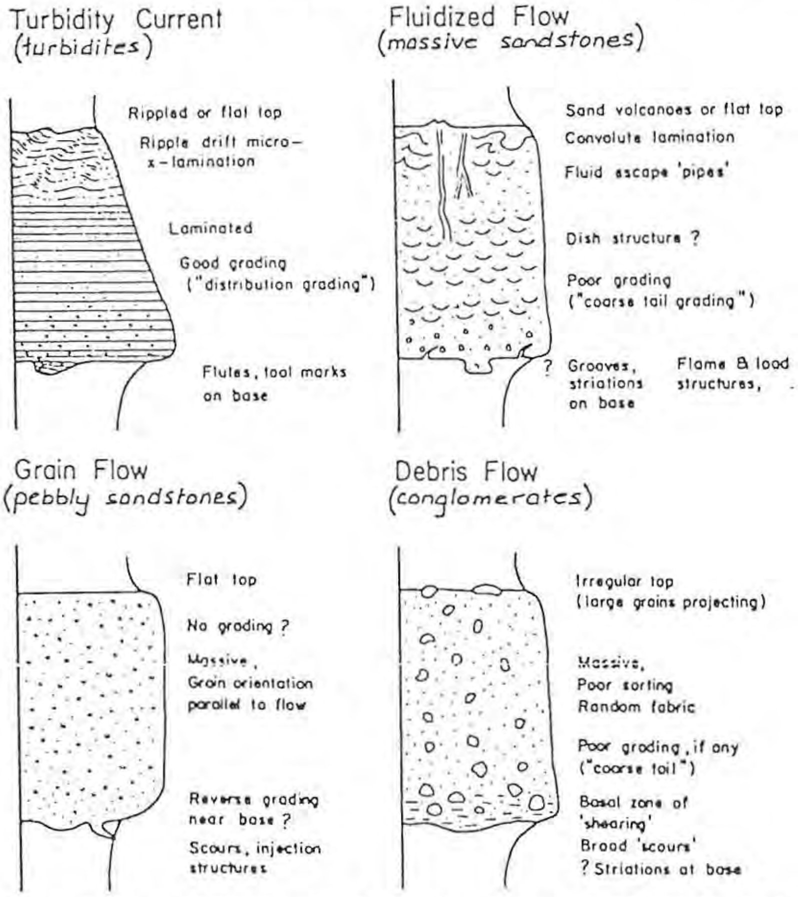


Figure 3.7 Schematic representation of sequence of sedimentary structures in the hypothetical single-mechanism deposits of the main types of gravity flows (after Middleton and Hampton, 1976) (Reineck and Singh, 1980)

d. Classic Turbidites and the Bouma Sequence

Characteristic features of turbidites include:-

1) a suite of sole marks or erosional features associated with the sharp base of each sandstone bed
2) a suite of internal sedimentary structures within each sandstone bed, including size grading, and massive to planar, cross or convoluted laminations
3) a covering pelitic or cherty layer on top of each sandstone
4) a bedding regularity such that individual beds may be traced for hundreds or thousand of meters laterally without appreciable thickness changes.

The ideal Bouma sequence, first described by Bouma (1962) is subdivided into "intervals" a to e. Not all turbidites may necessarily conform to a complete Bouma cycle e.g. turbidites may be described by intervals "b-c-d" and "c-d". However, intervals are rarely found in reverse order (Fig. 3.8). The Bouma sequence was later interpreted in terms of laboratory flow regimes (Fig. 3.6), (Middleton and Hampton, 1973).

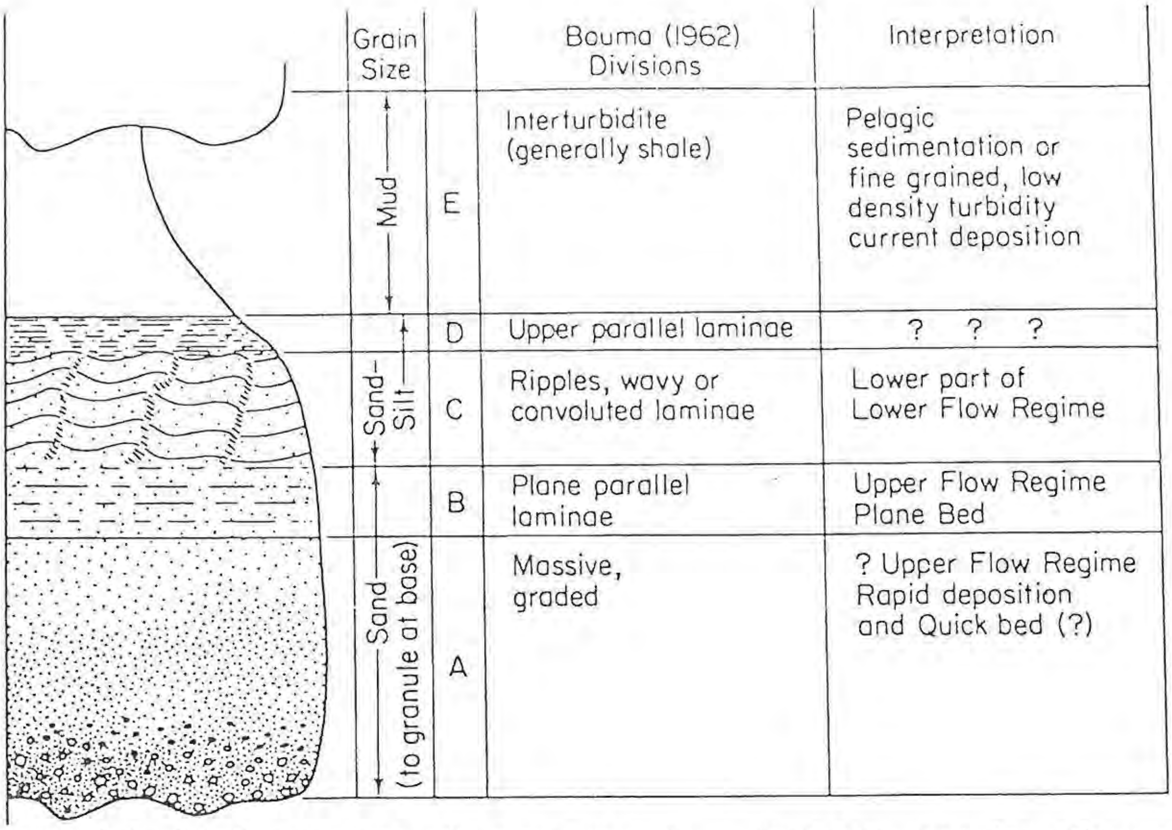
Sole marks are prominent in outcrops of classic turbidites and grouped into four types:-

1) scour markings (flutes are most important)
2) tool marks (grooves, striations, prod marks, bounce marks)
3) organic markings
4) load structures ("flame" structures, load-casted ripples and pseudo-nodules of sand in mud).

Both tool and scour marks are important for determining flow directions.

Dzulynski and Walton (1965) summarize a dazzling array of sedimentary structures found in turbidites and associated facies of which only the most important have been mentioned here (Figures 3.4 and 3.5).

Fabric studies showed that elongate particles (sand grains, plant fragments, graptolite remains) are often current aligned although these may diverge towards the top of a turbidite bed from the orientation of sole marks at the base. Such divergence is caused by meandering flow patterns in turbidity currents.



Grain Size		Bouma (1962) Divisions	Interpretation
Mud	E	Interturbidite (generally shale)	Pelagic sedimentation or fine grained, low density turbidity current deposition
Sand–Silt	D	Upper parallel laminae	? ? ?
	C	Ripples, wavy or convoluted laminae	Lower part of Lower Flow Regime
Sand (to granule at base)	B	Plane parallel laminae	Upper Flow Regime Plane Bed
	A	Massive, graded	? Upper Flow Regime Rapid deposition and Quick bed (?)

Figure 3.8 Ideal sequence of structures in a turbidite bed (the "Bouma sequence"). After Bouma (1962) and Blatt et al., (1972) (Middleton and Hampton, 1973)

Ancient turbidites generally have greywacke textures containing from about 15% to over 40% matrix. Only part of the matrix is primary while the rest is produced by diagenetic alteration or low-grade metamorphism of unstable grains (Rupke, 1978).

Compositionally turbidites may be both silicic and bioclastic, and often show the presence of ubiquitous spilitic fragments. Carbonate-rich turbidites, both in modern and ancient deep-sea basins are derived from bordering reefs and shelf areas. Shale layers between turbidites may contain deep-water benthonic and pelagic faunas (Rupke, 1978).

e. Modern Turbidite Fans

Large sedimentary cones situated on the deep sea floor adjacent to the slope break and seaward of most submarine canyons and major river deltas are formed by turbidity currents (Fig. 3.9). Deep sea fans, abyssal cones and submarine fans, which collectively represent types of fans and cones formed in the deep sea (or in lakes) by resedimentation processes are best referred to as turbidite fans (Rupke, 1978).

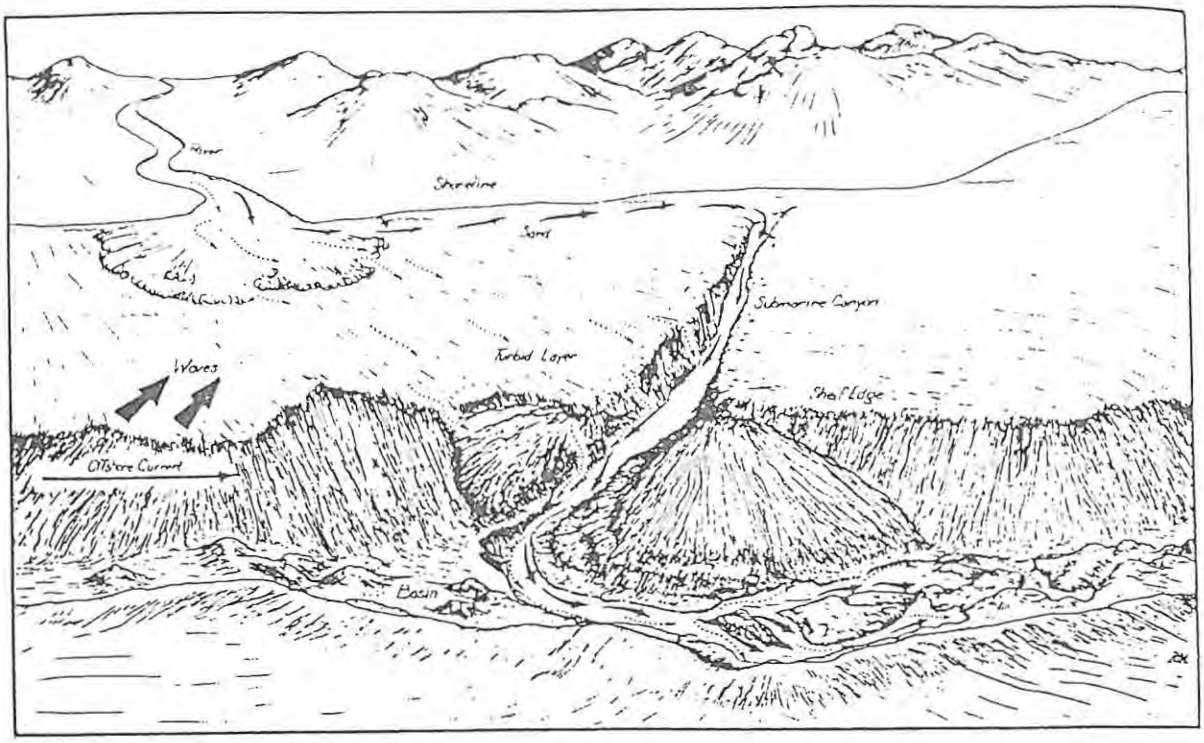


Figure 3.9 Schematic representation of the routes of transportation of sand (solid arrow) and mud (dotted arrow) from river mouth to deep-sea basin floor (after Moore, 1969) (Reineck and Singe, 1980)

Major turbidite fan formation requires (Nelson and Kulm, 1973):-

1) a sediment source, either provided by a large river system eroding continental shelves, volcanic islands, and carbonate banks, or littoral drift sediment captured by submarine canyon heads;

2) a submarine canyon system to funnel sediments into a deeper environment;

3) a decreasing bottom slope at the lower end of the canyon.

The turbidite fan surface consists of several distinct depositional environments and fan growth results from the interplay between mass flow processes and the depositional topography which includes channels, levees and interchannel areas. Although fan deposition implies symmetry, frequently this is not the case. Turbidite fans are subdivided into (Fig. 3.10):-

1) an <u>upper fan</u> (suprafan) environment, characterized by rugged topography and a single deep channel or main fan valley with levees;

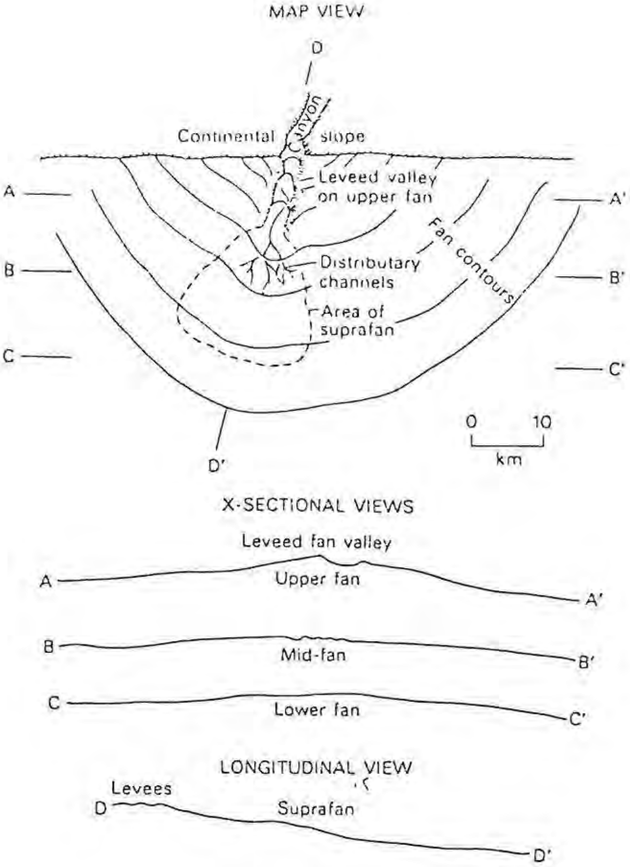


Figure 3.10 Model of the physiography of a turbidite fan, based largely on the characteristics of deep-sea fans off the west coast of North America (from Normark, 1970) (Nelson and Kulm, 1973)

2) a middle fan environment of hummocky topography where the main channel splits into a number of fan channels. Channels either meander or braid, are active or become abandonned and usually terminate in depositional lobes;

3) a lower fan environment (or outer fan), which is topographically smooth with numerous small channels without levees (Walker 1978; Rupke, 1978).

Fan valleys and channels may be depositional, erosional or mixed depositional-erosional (Nelson and Kulm, 1973).

Classic turbidite facies characterize the smooth middle fan lobes and lower fan while massive and pebbly sandstones occupy the braided channel parts. Coarse sedimentation involving mass gravity transport other than turbidity currents is restricted to the upper fan channel where conglomerates with gravel- and boulder-size clasts accumulate. Fine-grained sedimentation may occur laterally by overflow onto levees and into interchannel areas (Walker, 1978; Rupke, 1978).

A model showing the distribution of turbidite facies is presented in Figure 3.11.

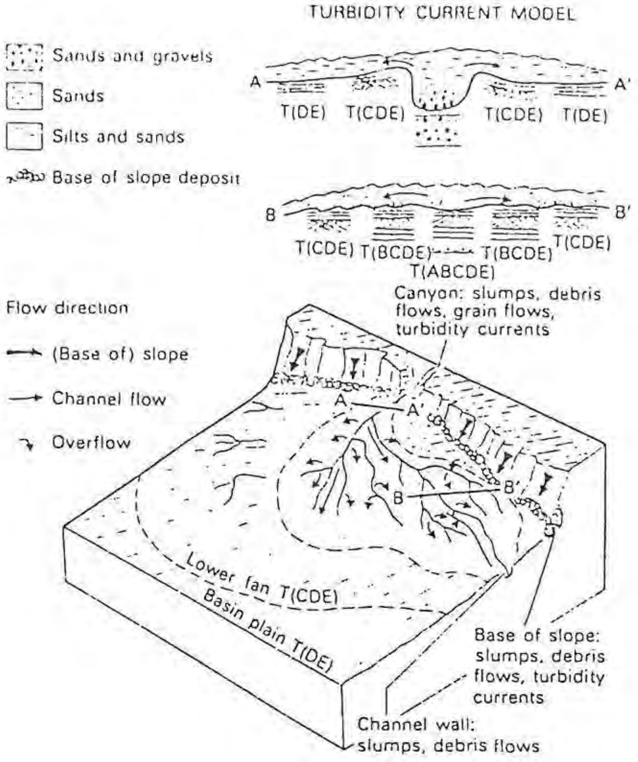


Figure 3.11 Bi-modal channel and overbank deposition by turbidity currents across a turbidite fan. The model is largely based on the Astoria Fan and uses Bouma sequences A to E (Nelson and Kulm, 1973)

Lateral shifting of prograding depositional lodes produces the overall fan-shape. Abandonment of one lobe for another is recognized by blanket mud deposition on the abandonned lobe. Shifting either takes place gradually or catastrophically resulting in emplacement of turbidite sands on top of interchannel muds. Growth of a turbidite fan is influenced by the open or restricted physiography of the depositional basin, lattitude, sea-level fluctuation, tectonic history of the basin, nature of sediment source and presence or absence of indigenous bottom currents (Rupke, 1978).

Flysch and Ancient Turbidite Fans

"Flysch" is presently accepted as a facies term used to describe any thick succession of redeposited deep sea detritus (Rupke, 1978). Confusion with the term arose when it was believed that turbidites which may be deposited in shallow water are diagnostic of flysch facies. Clearly isolated sedimentary structures typical of turbidites may be also produced from other types of episodic flow other than turbidity currents. Deep-sea origins for flysch facies are suggested by the following:-

1) Thick successions of redeposited clastics only accumulate in modern deep sea environments.
2) Fossils range from shallow shelf, littoral to bathyl and deep basin assemblages, of which the latter is most common.
3) Deep-water benthonic foraminifera often occur in hemi-pelagic shales between turbidite sandstone.

Palaeocurrent analysis of flysch turbidites led to the discovery of longitudinal filling, a fundamentally important concept with palaeogeographic reconstructions of geosynclinal belts. A number of studies through the 1960's confirmed the model of axial (or longitudinal) and marginal (or transverse) trough fill. Palaeocurrent analysis also made possible the tracing of lithological changes in a downcurrent direction and thus differentiate depositional environments both close to and further away from the source (proximal versus distal). A turbidite sequence changes in a downcurrent direction with respect to decreasing sandstone-shale ratio, sandstone thickness, grain size and erosive features; flutes become fewer and tool marks increase in number. Using the Bouma sequence a single turbidity current deposits under increasingly lower flow regimes in a downcurrent direction (Fig. 3.12, Rupke, 1978).

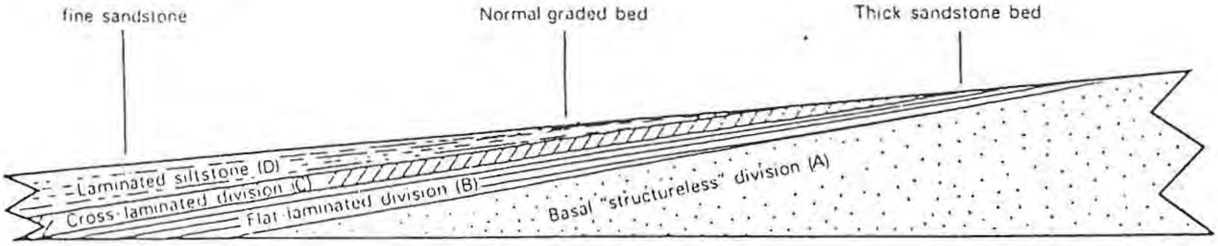


Figure 3.12 Idealized variations in a single turbidite bed (after Corbett, 1972) (Rupke, 1978)

A turbidite facies classification from A to G proposed by Walker and Mutti (1973) used the following criteria:- bed thickness, grain size, sandstone-shale ratio, bedding regularity, sole-marking assemblages, internal structures and textures and palaeoecological indicators. The scheme enabled rapid, factual description and comparison between flysch-type sedimentary basins (Table 3.1) (Eriksson, 1982; Glikson, 1971).

Table 3.1 Basic classification of turbidite and other resedimented facies, based upon Mutti and Ricci Lucchi (1972) and Walker (1967, 1970 and Unpublished) (Walker and Mutti, 1973)

BOUMA SEQUENCE NOT APPLICABLE	FACIES A -- Coarse grained sandstones and conglomerates A1 Disorganized conglomerates A2 Organized conglomerates A3 Disorganized pebbly sandstones A4 Organized pebbly sandstones.
	FACIES B -- Medium-fine to coarse sandstones B1 Massive sandstones with "dish" structure B2 Massive sandstones without "dish" structure.
BEDS CAN REASONABLY BE DESCRIBED USING THE BOUMA SEQUENCE	FACIES C -- Medium to fine sandstones -- classical proximal turbidites beginning with Bouma's division A.
	FACIES D -- Fine and very fine sandstones, siltstones -- classical distal turbidites beginning with Bouma's division B or C.
	C-D FACIES SPECTRUM -- can be described using the ABC index of Walker (1967).
	FACIES E -- Similar to D, but higher sand/shale ratios and thinner more irregular beds.
BOUMA SEQUENCE NOT APPLICABLE	FACIES F -- Chaotic deposits formed by downslope mass movements, e.g. slumps.
	FACIES G -- Pelagic and hemipelagic shales and marls -- deposits of very dilute suspensions.

The turbidite fan model and facies classification were applied to flysch successions ever since the similarity between ancient fan environments and modern fans was recognized (Fig. 3.13). The fan model in flysch study uses

1) palaeocurrent analysis
2) study of proximal facies, and
3) vertical sequence analysis.

The presence of a radial palaeocurrent pattern normally characterizes ancient fans although normally fan shape is difficult to demonstrate. Proximal facies are characterized by thick-bedded, coarse-grained mass flow deposits (other than turbidites), which exhibit abrupt facies changes perpendicular to radial palaeocurrent directions from elongate sandstone or conglomerate bodies to finer silt- and mudstones (Rupke, 1978).

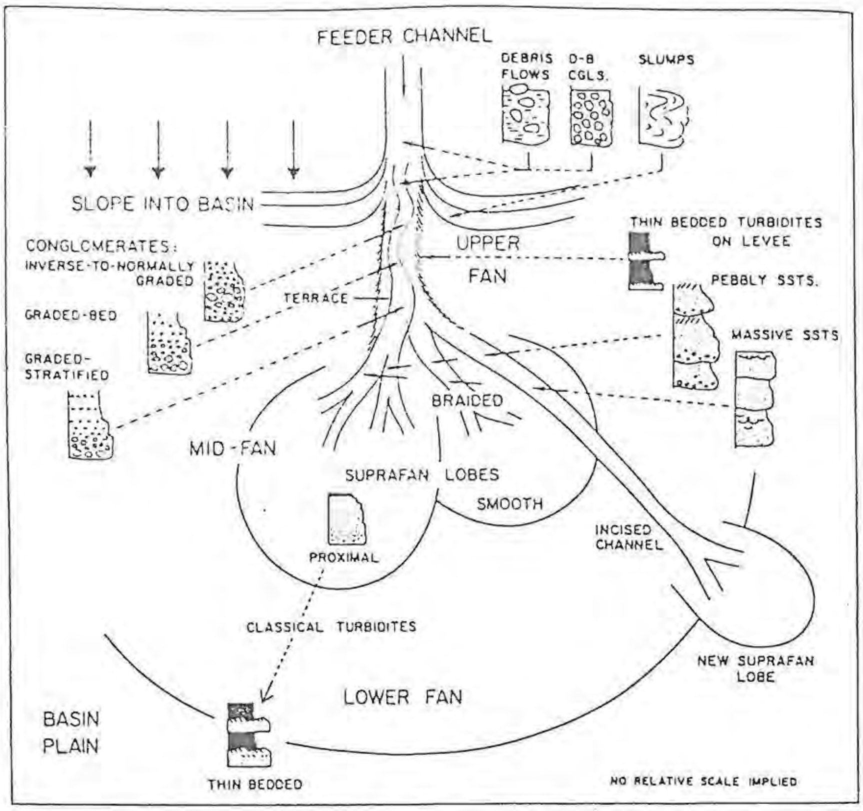


Figure 3.13 Model of submarine-fan deposition, relating facies, fan morphology, and depositional environment. D-B indicates disorganized-bed conglomerates (Walker, 1978)

Sequence analysis enables the description of thick turbidite successions and differentiation between basin plain, fan, slope and shelf sediments. Cyclicity of turbidite sequences suggests regularity of the sedimentation process although random events at any stage may disrupt any apparent cycle (Fig. 3.14, Reading, 1978). Thickening- and coarsening-up sequences reflect prograding fan deposition whereas thinning-up sequences characterize lateral migration or gradual abandonment of a channel. Sequences characteristic of upper, middle and lower fan facies are presented in Figure 3.15.

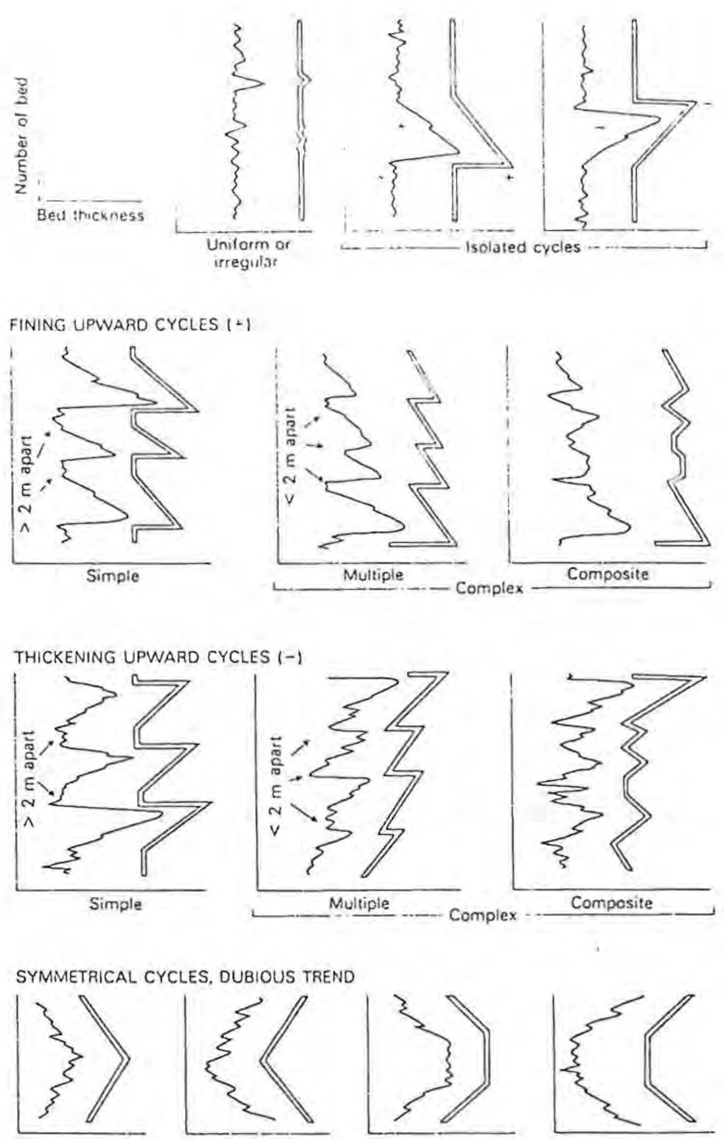


Figure 3.14 Types of vertical sequences of the order of 10-100m in ancient turbidite fans (from Ricci-Lucchi, 1975b) (Rupke,

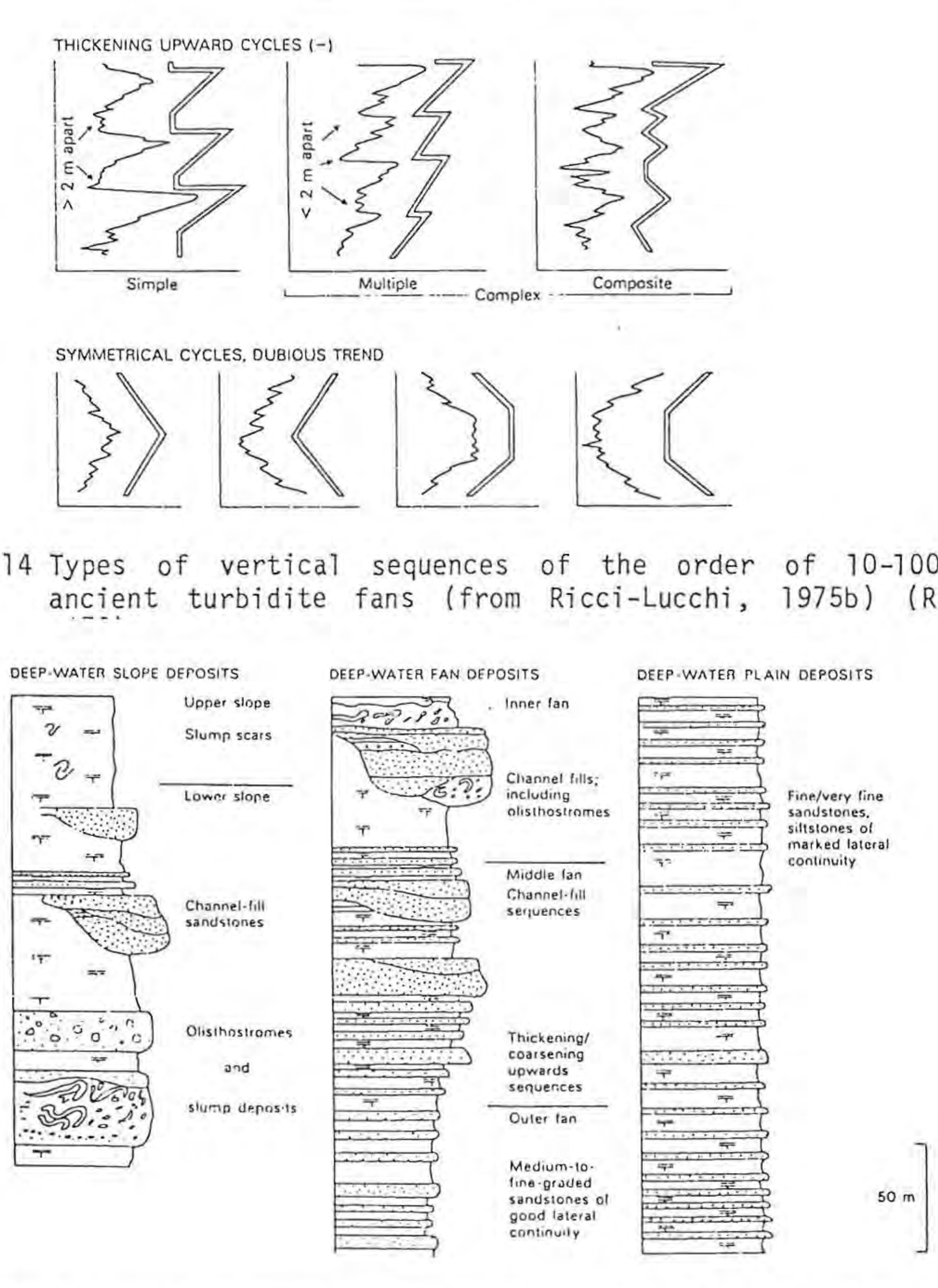


Figure 3.15 Sequences characteristic of slope, fan and basin plain facies (after Mutti and Ricci-Lucchi, 1972) (Rupke, 1978)

4.0 GEOTECTONIC SETTING OF TURBIDITES

a. Plate Tectonics and Turbidites

The most extensive turbidite or modern basin plains are situated seaward of major drainage basins and represent the ultimate trap for eroded sediments. Source sediments feed basin plains via submarine canyons, deep sea channels or surrounding basin slopes. Lithofacies of basin plains vary from turbidite sand, silt and mud beds to hemi-pelagic muds. Syn-sedimentary deformation such as sliding and slumping, is largely restricted to basin, slope and rise environments (Rupke, 1978).

Using basin physiography, modern basin or turdibite plains may be classified as (Fig. 4.1):-

1) open oceans
2) deep sea trenches
3) enclosed seas
4) borderland basins
5) miscellaneous including oceanic ridge basins and lakes (Rupke, 1978).

Dickinson (1974) preferred to describe sedimentary basins in terms of the type of substratum beneath the basin viz. oceanic, continental, or transitional. In this way the proximity of a basin to a plate margin and the type of plate junction nearest the basin is described. Turbidite basins may be either associated with:-

1) Rifted margin prisms - miogeosynclinal near-shore facies resting on continental basement grade to eugeosynclinal off-shore deep water turbidites, which in turn grade to oceanic basin deposits.

2) Arc-trench systems - eugeosynclinal terranes are associated with magmatic arcs, trenches and oceanic strata. Lithologies are mingled tectonically as sediments are detached from the tops of subducting slabs of lithosphere.

In summary modern plate tectonic settings where turbidites might be expected include rift-related, subduction-related or transform fault-related environments (Mitchell and Reading, 1978).

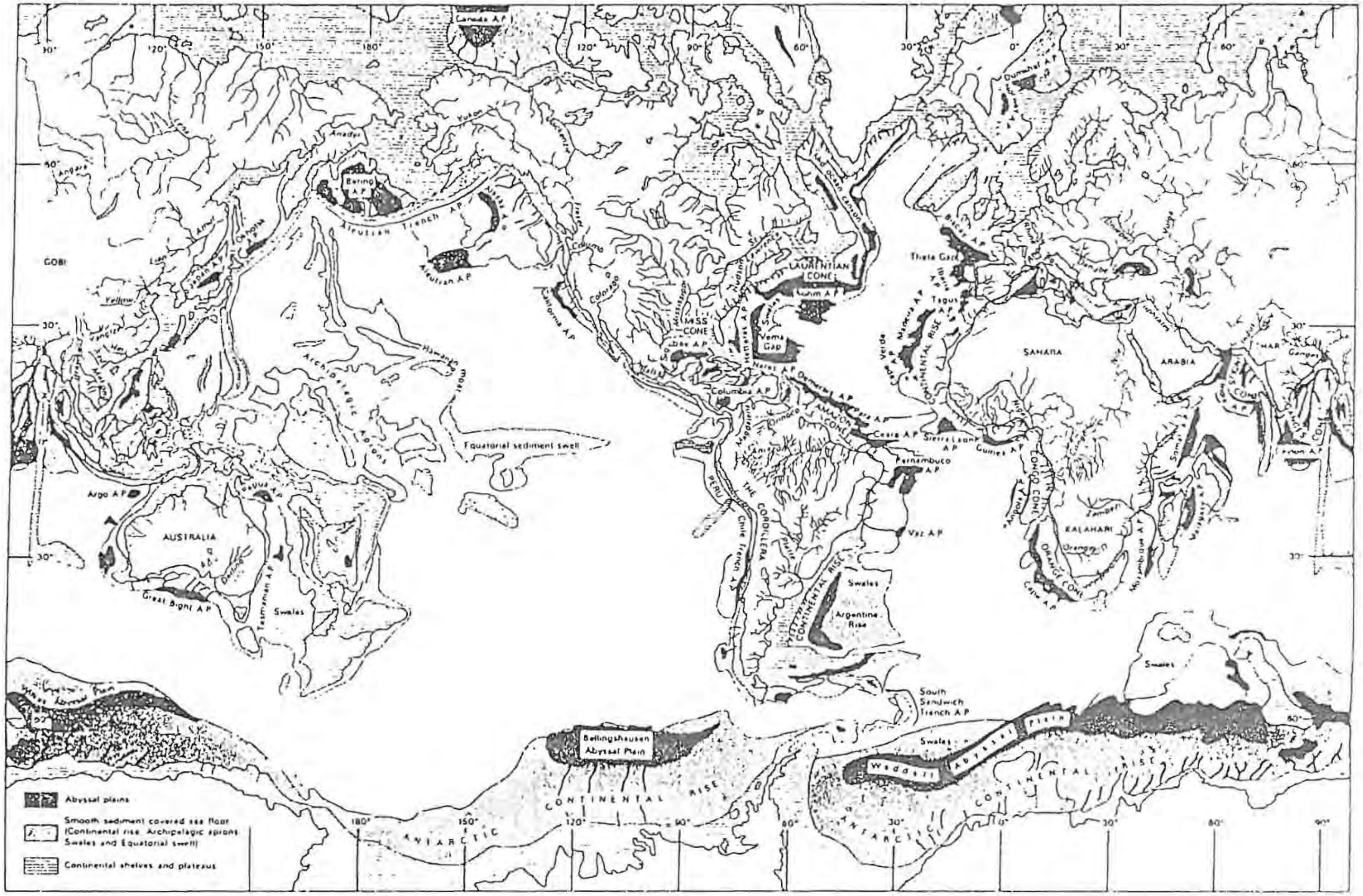


Figure 4.1 World distribution of major deep-sea basin plains and abyssal cones (from Heezen and Hollister, 1971) (Rupke, 1978)

Rift-related Settings

Distinct sedimentary facies characterize the evolution of continental rifts through four principal stages. The narrow ocean and Atlantic stages are the most important for accumulation of turbidites (Boillot, 1981, Fig. 4.2). Failed rifts may form aulacogens e.g. the Tertiary-aged Benue Trough,

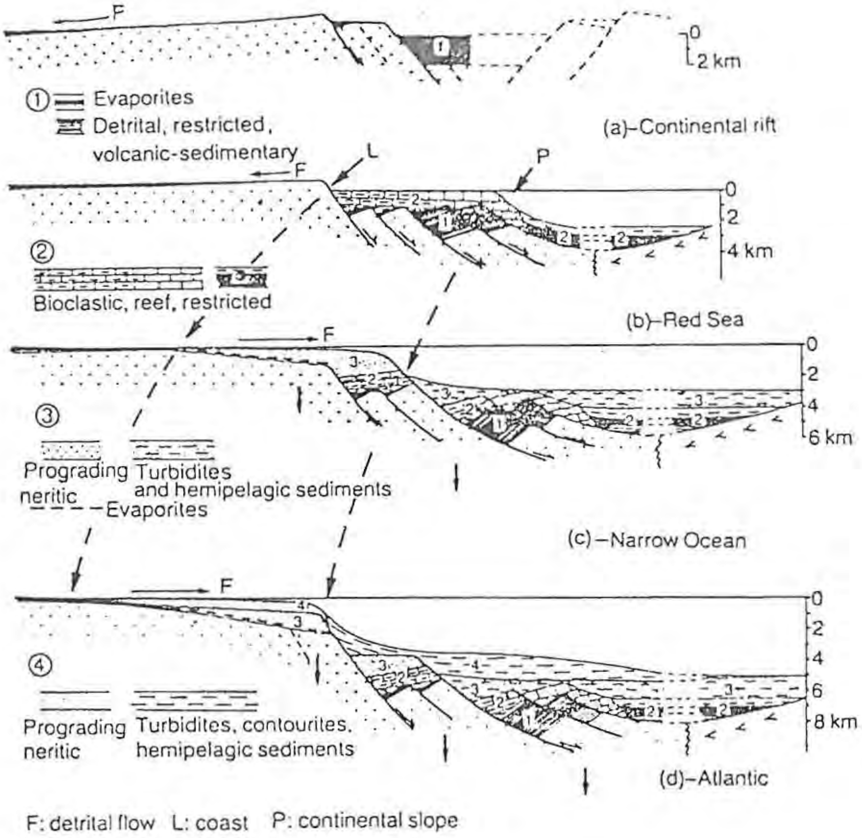


Figure 4.2 The four principal stages in the evolution of a stable continental margin (the case of European Atlantic margins) (Boillot, 1981)

which is filled with over 10km of sediment passing from submarine fan deposits (turbidites) through deltaic to fluvial facies. Rifting otherwise evolves to form a major ocean basin e.g. the Atlantic ocean (Mitchell and Reading, 1978).

Rupke (1978) noted the relative abundance of turbidite basin plains in the Atlantic and scarcity along Pacific ocean margins (Fig. 4.1). Atlantic continental margins are predominantly passive, whereas Pacific continental margins are mostly active and characterized by arc-trench systems. These act as barriers or traps to terrigenous sedimentation. Passive continental margins have a slope and rise where muds, silts, and fine sands are deposited by low density turbidity currents (turbidites) or ocean bottom contour currents (contourites). Close to the shelf edge coarse turbidites and other mass flow deposits accumulate (Fig. 4.3). Large scale rotational sliding and slumping on passive continental margins may cause the absence of sediment on some parts of the continental slope.

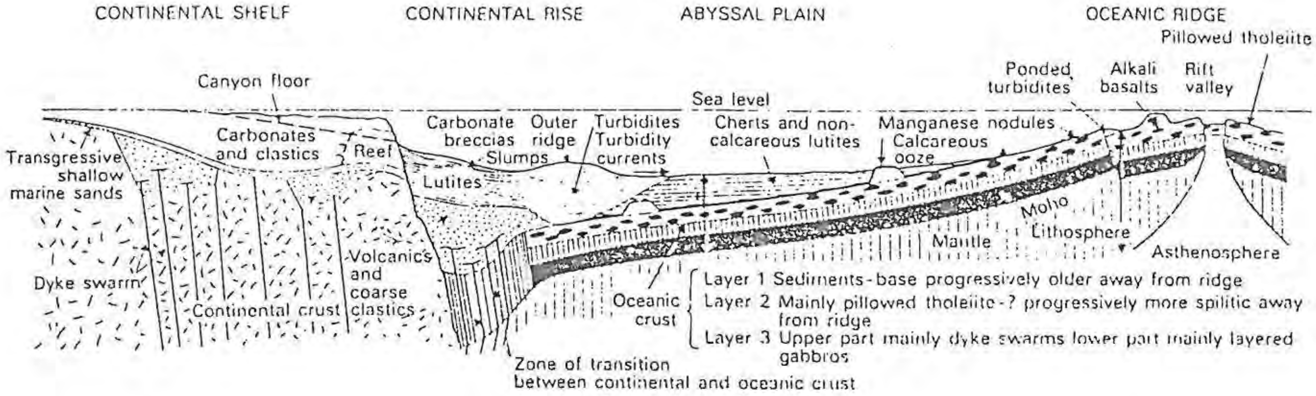


Figure 4.3 Cross-section of the western Atlantic showing relationships of continental crust, oceanic crust and sediments (from Dewey and Bird, 1970) (Mitchell and Reading, 1978)

The narrow ocean stage represents a relatively restricted environment due to limited oceanic circulation. Turbidites are therefore often intercalated with hemipelagics and preserved particles of organic origin. The proportion of preserved organic matter in black shales may increase considerably when detrital influx from the continent contains abundant debris of vegetal origin (Fig. 4.4, Boillot, 1981).

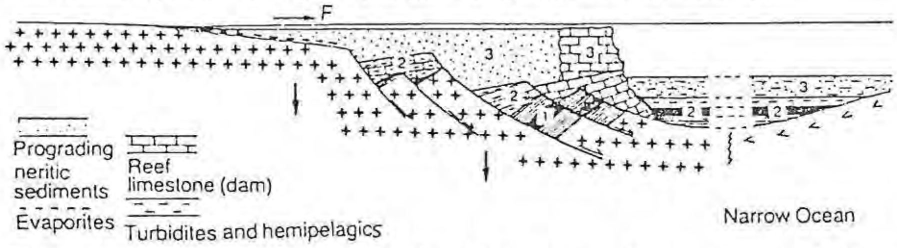


Figure 4.4 The 'narrow ocean stage' in the case where a coral barrier is built upon the shelf-edge (the Atlantic margin of the United States) (Boillot, 1981)

Subduction-Related Settings (Fig. 4.5)

1) Fore-arc areas, including the arc-trench gap or accretionary prism, and the trench may comprise either a simple slope e.g. the Marianas, or a sedimentary prism not topographically apparent. Otherwise known as the outer arc ridge or trench slope break, the sedimentary prism is separated from the volcanic arc by an outer arc trough or fore-arc basin.

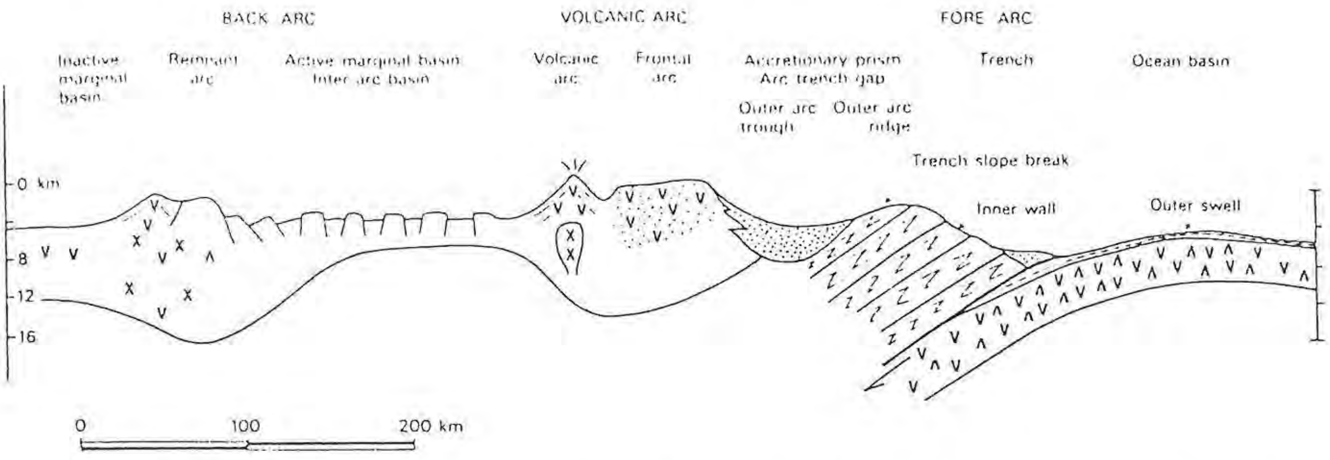


Figure 4.5 Generalized cross-section of intra-oceanic island arc (Mitchell and Reading, 1978)

Trenches were originally thought the sites of ancient geosynclines but modern examples of both deep and shallow trenches accumulate sediments only up to 2km in thickness (Rupke, 1978). Substantial thicknesses of geosynclinal turbiditic sediments are more apparent than real and largely the consequence of tectonic thickening. Turbidites deposited on the trench axis are preferentially sheared off underlying pelagics and oceanic crust during subduction and accreted to the lower trench wall (Fig. 4.6, Karig and Sharman III, 1975). Tectonic repetition and accretion of a relatively thin turbidite wedge may be sufficient to form a major outer arc.

Trenches represent the deepest and most elongate of oceanic basins, extending for sometimes hundreds of kilometres but only a few tens of kilometres across. Seismic and volcanic activity mark the landward size of the trench (magmatic island arc or Andean arc) and both landward and seaward sides of the trench are faulted. The trench floor is often tectonically broken into compartments and therefore parts may be sediment starved. High relief of the source area and the presence of volcanic activity results in compositionally immature clastics which are dispersed by longitudinal turbidity currents. Slumping perpendicular to these currents is common (Fig. 4.7, Rupke, 1978).

2) Outer arc troughs may accumulate sediments exceeding 5km in thickness in the 50-100km wide zone between the tectonically emplaced outer arc region and magmatic arc. On the magmatic arc side sediments may interfinger with volcanics.

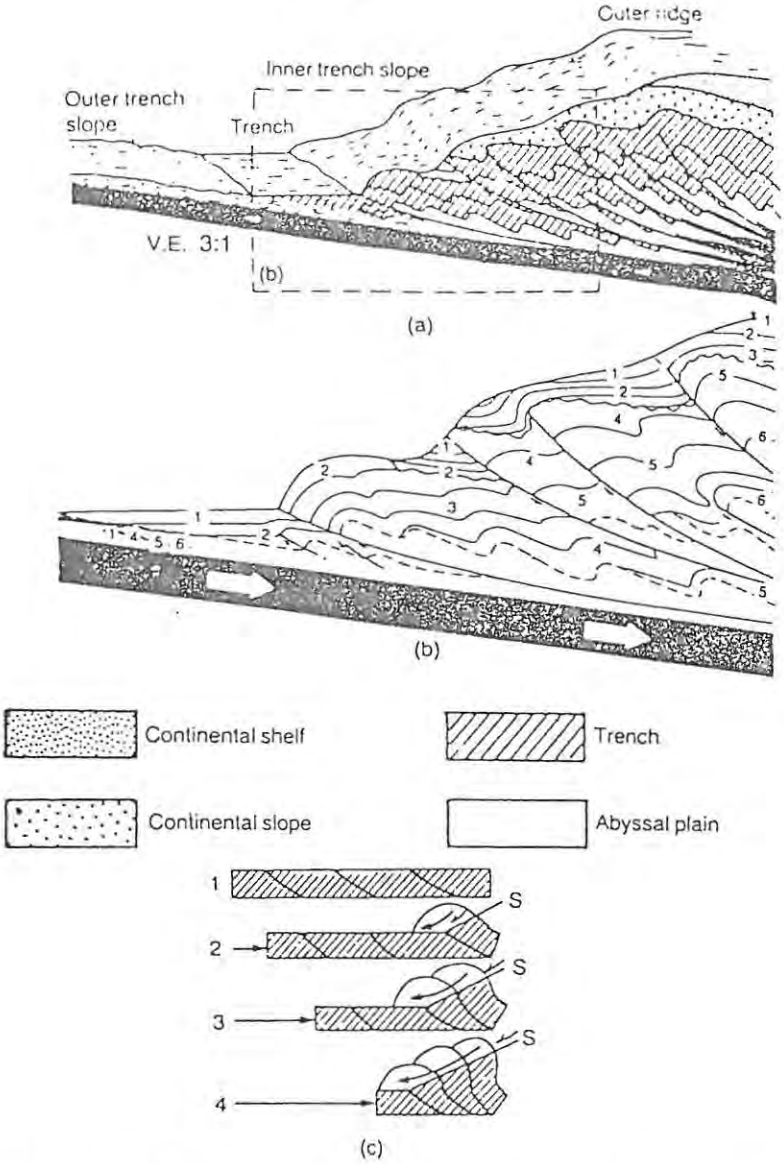


Figure 4.6 Model of tectonic accretion. (a) distribution of facies; (b) distribution of isochrons (stratigraphy). Numbered sequences go from the youngest to the oldest beds. The dotted line represents the boundary between turbidites in the trench and sediments in the abyssal plain. (c) interpretative diagram; S: slip-surface for sediments slumping down the inner trench slope and thus feeding turbidites in the trench; 1 to 4: successive stages of tectogenesis determined by plate convergence (after Seely et al., 1974) (Boillot, 1981)

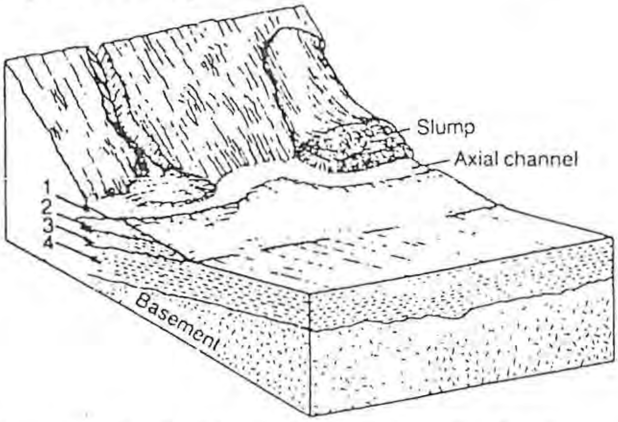


Figure 4.7 Schematic, distribution of sediment facies in the Aleutian Islands trench. 1: coarse turbidites; 2: sand, silt, mud. 3: silt and mud; 4: abyssal plain: silt and mud (after Piper et al., 1973) (Boillot, 1981)

Clastic sedimentation predominates but varies with different troughs from turbidite, deltaic to fluvial. Sediments are derived from three source areas: laterally from outer and magmatic arcs, and longitudinally from adjacent continents. Commonly belts of flysch sediments are interbedded with ultrabasic rock (ophiolites) e.g. the intradeeps of the Sunda arc.

3) Volcanic arcs. Volcanogenic turbidites are commonly encountered in environments of tholeiitic to calc-alkaline volcanism. Facies change from epiclastic and pyroclastic rocks and volcanic flows, to thick wedges of conglomerate and mass flow volcanoclastics, to turbidites and pelagics.

4) Back arc environments are characterized by a range of sedimentary facies which are similar to major and narrow oceanic basins (Mitchell and Reading, 1978). Dickinson (1974) differentiated the back arc region into inter-arc and retro-arc basins which are floored by oceanic and continental crust respectively. Turbidity currents in these mediterranean or marginal sea environments are fed from a variety of sources, both silici-clastic and bioclastic sources being common (Rupke, 1978).

Transform Fault-Related Settings

Lateral shear during continental collision may cause compression and tectonic crustal thickening near pullapart basins. Erosion of uplifted terrane into the basins may deposit turbidites in submarine fans which pass upward into continental clastics such as molasse (Mitchell and Reading, 1978). These borderland basins are usually small and shallow with flat basin floors (Fig. 4.8).

b. Gold-Hosting Turbidites in the Geological Record

Goldfields in turbidites occur throughout the geological time record. By reviewing the geotectonic setting of selected goldfields it is hoped that of the broad spectrum of plate tectonic environments which accumulate geosynclinal successions, some might be noticeably more prospective for concentrating gold.

Archaean Greenstone Belts

Turbidite successions commonly dominate the sedimentary cycle of Archaean greenstone belts. Stratigraphically greenstone belts evolve through

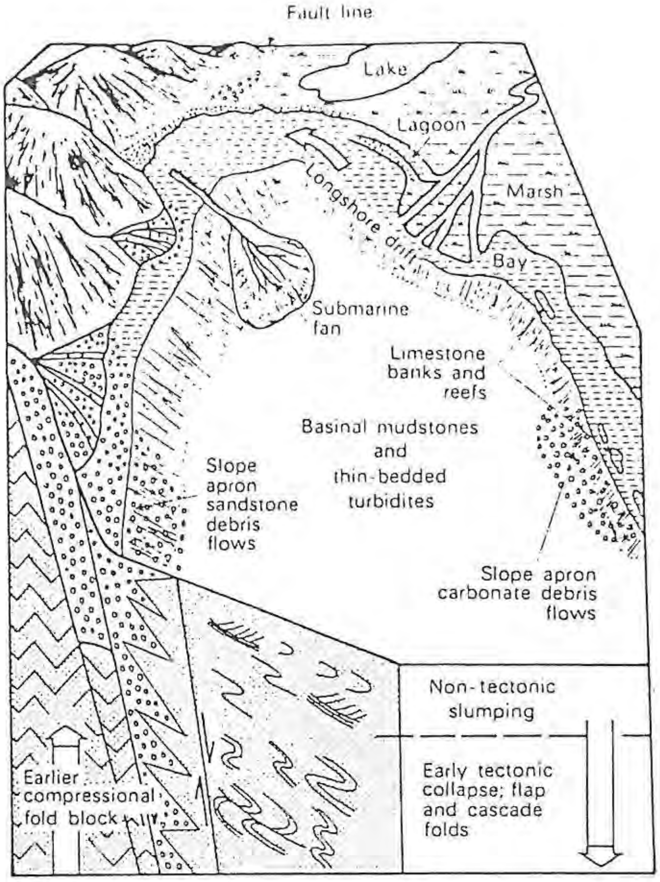


Figure 4.8 Sedimentary and tectonic model for a strike-slip orogenic basin (Mitchell and Reading, 1978)

ultramafic-mafic, calc-alkaline volcanic and sedimentary successions (Anhaeusser, 1976). Recognition of turbidites in the Barberton Mountain Land (Eriksson, 1980a, 1980b, 1981), the Kalgoorlie System (Glikson, 1971) and Pilbara Block of Western Australia (Eriksson, 1981, 1983) placed constraints on models of Archaean greenstone belt formation.

Important gold producers, such as Fairview and various mines of the Sheba group in the Barberton greenstone belt are hosted in turbidite sequences of the Figtree Group. Eriksson (1980b) proposed that lithologic and palaeoenvironmental inter-relationships within the deepwater facies of the Fig Tree Group and shallow water facies of the Moodies Group were best accommodated within an evolving back-arc or passive continental margin. A steep rift margin was succeeded by development of a stable continental shelf through outbuilding of a turbidite wedge and was probably enhanced with a eustatic rise in sea level. Extensive tidal flat, deltaic and barrier beach sediments of the Moodies Group then accumulated on that shelf (Eriksson, 1981).

Glikson (1971) on the basis of facies transitions (pelitic to greywacke-slate to greywacke-conglomerate) also postulated a rifting environment for the Eastern Goldfields of Kalgoorlie. Emerging source terranes were flanked by rapidly subsiding troughs.

Mosquito Creek Group turbidites of the Pilbara host less important gold mineralization at various prospects including Blue Spec. Eriksson (1981) noted a shallow to deep water transition in both the Mosquito Creek and Budjan Creek belts which implied a continental to marine transition along a narrow continental shelf.

Palaeogeographic reconstructions in the Barberton, Kalgoorlie and Pilbara regions support classic rift models proposed for Archaean greenstone belt evolution (Fig. 4.9). These are compatible with a recent plate tectonic model proposed by Windley, (1984) in which greenstone belts developed in extensional back-arc basins (Fig. 4.10).

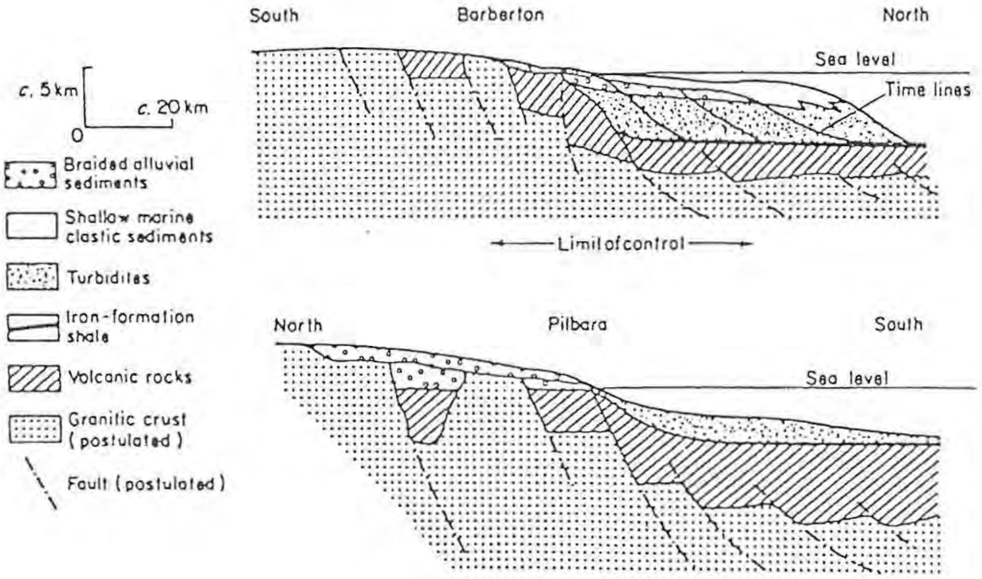


Figure 4.9 Schematic palaeographic reconstruction in Barberton and Pilbara greenstone belts (from Bickle and Eriksson, 1982) (Windley, 1984)

Proterozoic Orogens

The Ashanti goldfield of Ghana lies in the Early Proterozoic Birimian succession of thick greywacke-shale sequences, volcano-sedimentary rocks and younger shallow water clastics. The favoured tectonic model for the Birimian approximates a typical model for greenstone belts, although Hastings (1982) suggested that Ghana which forms the type area for the Eburnian tectonic province should not be strictly equated with Archaean greenstone belts. Windley (1984) who differentiated Early to Middle

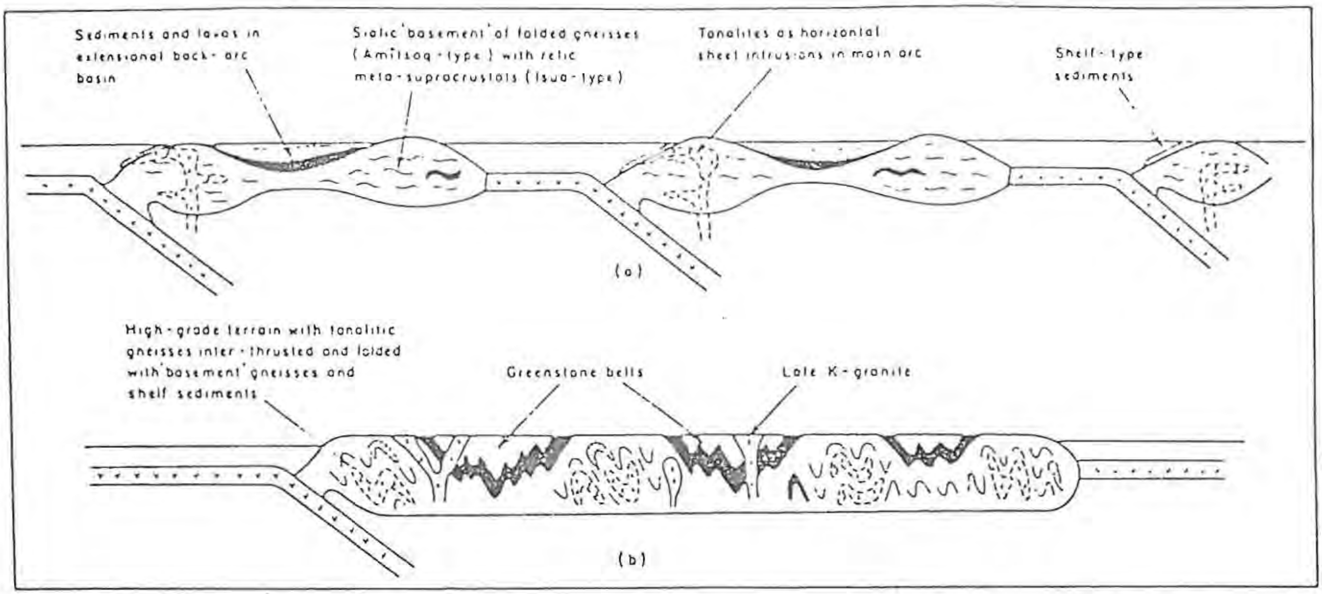


Figure 4.10 A plate tectonic model to explain the growth of continents in the Archaean. (a) Widespread lateral movement of many early Archaean mini-continental plates with shelf-type quartzites, carbonates, and K-pelites and with mantle-derived tonalites in batholithic proportions in proto Andean-type arcs and of volcanics in back-arc environments. (b) Aggregation of mini-continents gives rise to extensive continental plate by the end of the Archaean consisting of greenstone belts, and granulite-gneiss belts with older and younger gneissic components. Amphibolite- to granulite-grade metamorphism (heat flow) and deformation of tonalites to give rise to tonalite gneisses takes place in the roots of the main arc (Windley, 1984)

Proterozoic supracrustals into three main lithological assemblages, identified the Birimian successions of Ghana as a calc-alkaline volcanic-greywacke assemblage of back-arc, intra-arc and fore-arc basin origin.

Greenstone belts of Early Proterozoic age have been well documented by Windley (1984) and may represent a significant target for gold exploration considering their similarity to the Archaean.

The geotectonic setting of the Mid-Proterozoic Telfer gold deposit of the Paterson Province, Western Australia may be best described as part of the Bangemall Basin, a later development of the aulacogen feature known as the Capricorn Orogen (Gee, 1979). The Capricorn Orogen developed as an ensialic geosyncline on gneissic basement between the Pilbara and Yilgarn Archaean cratons and formed the site of Early Proterozoic (2000-1600Ma) trough sedimentation, prograde metamorphism, basement reworking, multiple deformation and granitoid emplacement. The intracratonic Bangemall Basin was superimposed on the Capricorn Orogen around 1100-1000Ma. Representing a typical Mid- to Late-Proterozoic basin, the Bangemall is characterized by shallow water continental margin assemblages which were succeeded by collapsing of carbonate banks and deep-water flysch-type accumulation (Yeneena Group) to the north and overlapping the older Paterson Orogen (Windley, 1984; Goode and Hall, 1981, Goode, 1981) (Fig. 4.11).

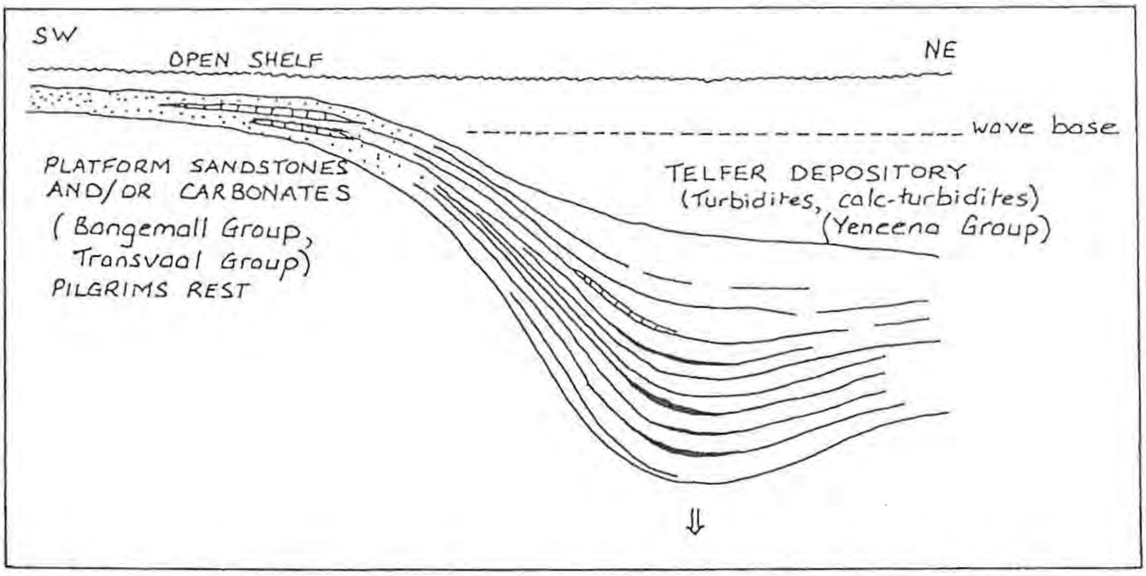


Figure 4.11 Hypothetic section showing the facies relationships during deposition of the Bangemall Basin, Western Australia

Palaeozoic Geosynclines

Subduction-related geotectonic settings are favoured for important goldfields hosted in turbidites of the Palaeozoic Lachlan Fold Belt (Tasman Geosyncline) in Victoria. The Tasman Geosyncline or Fold Belt of Eastern Australia is a composite tectogenic system composed of several segments (fold belts or orogens) and believed to represent the remains of individual lithospheric blocks. These subplates or tectonic provinces, now welded to the Australian plate were marginal mobile zones during the Palaeozoic, when tectonic activity was probably similar to that operating presently in the South West Pacific (Scheibner, 1978). The Lachlan Fold Belt or Province comprises the most south-eastern portion of the Tasman Geosyncline extending from Tasmania, through most of Victoria and much of New South Wales. Interpretations for the geotectonic evolution of the Lachlan Province vary (Packham and Leitch, 1974; Solomon and Griffiths, 1974; Crawford and Keays, 1978). Crook (1980) postulated a model of inner fore-arc evolution for the Ballarat and Melbourne Troughs of the Lachlan Fold Belt. However, recent palaeogeographic reconstructions are more compatible with a subduction- related, arc-back arc setting as proposed by Powell (1983) (Fig. 4.12).

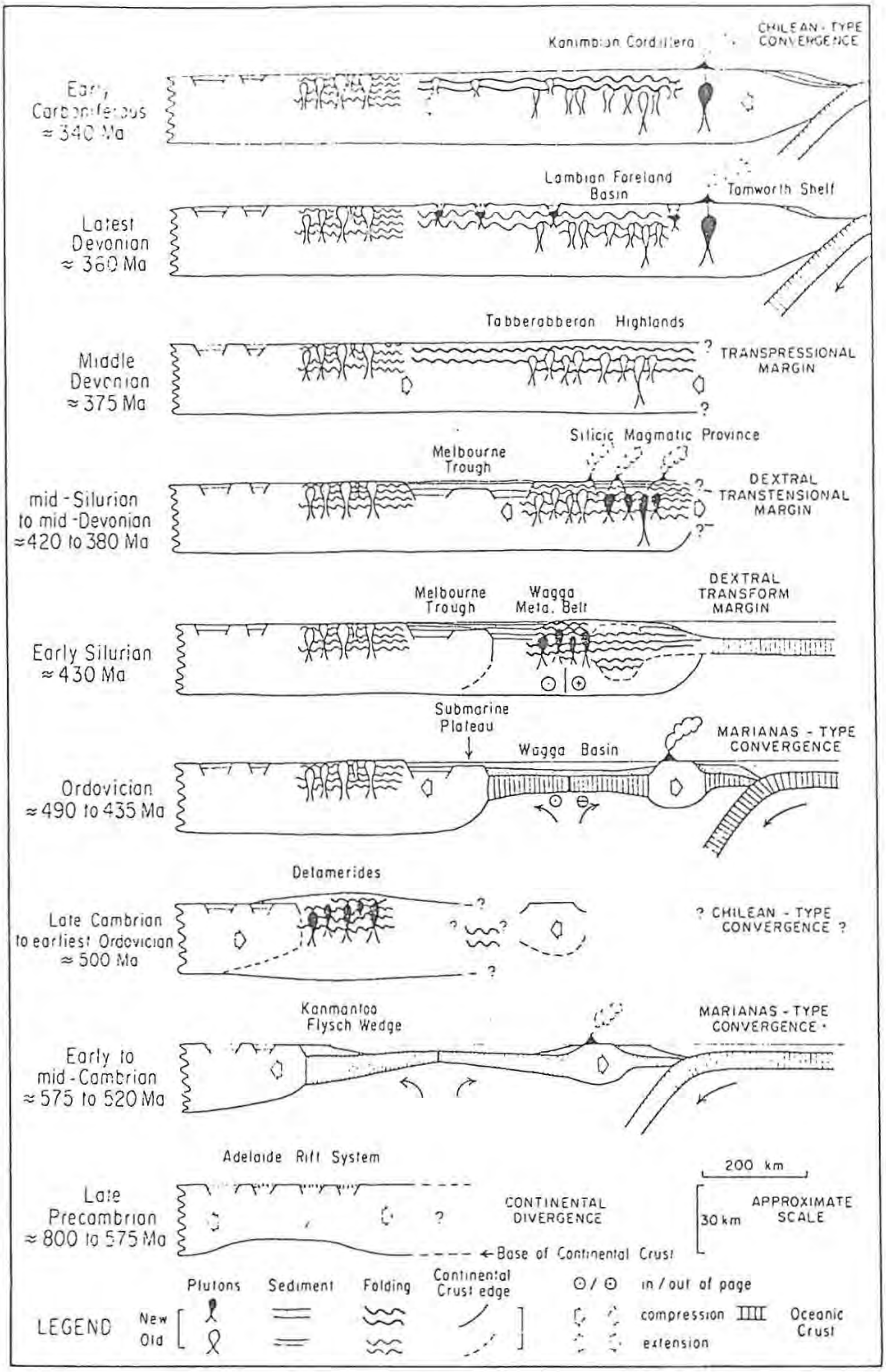


Figure 4.12 Cartoon showing a plate-tectonic interpretation of the development and ultimate stabilization of the Lachlan Fold Belt. E-W sections are drawn at a latitude of about 36°S, with some elements projected onto profile along tectonic strike. Scale is very approximate (Powell, 1983)

The Central Victorian troughs developed as part of the Wagga Basin between the Ordovian and Mid-Silurian. Eugeosynclinal sequences of the Greenland Group of West Nelson, New Zealand are often associated with intercalated mafic volcanics or spilites. Believed to represent the remnants of a volcanic arc, spilites erupted during post-arc deposition of turbidites in either back-arc or magmatic arc geotectonic settings (Fig. 4.13A or 4.13C). A fore-arc model of evolution is presently favoured for the Tuhua Terrane of New Zealand (Crook and Feary, 1982).

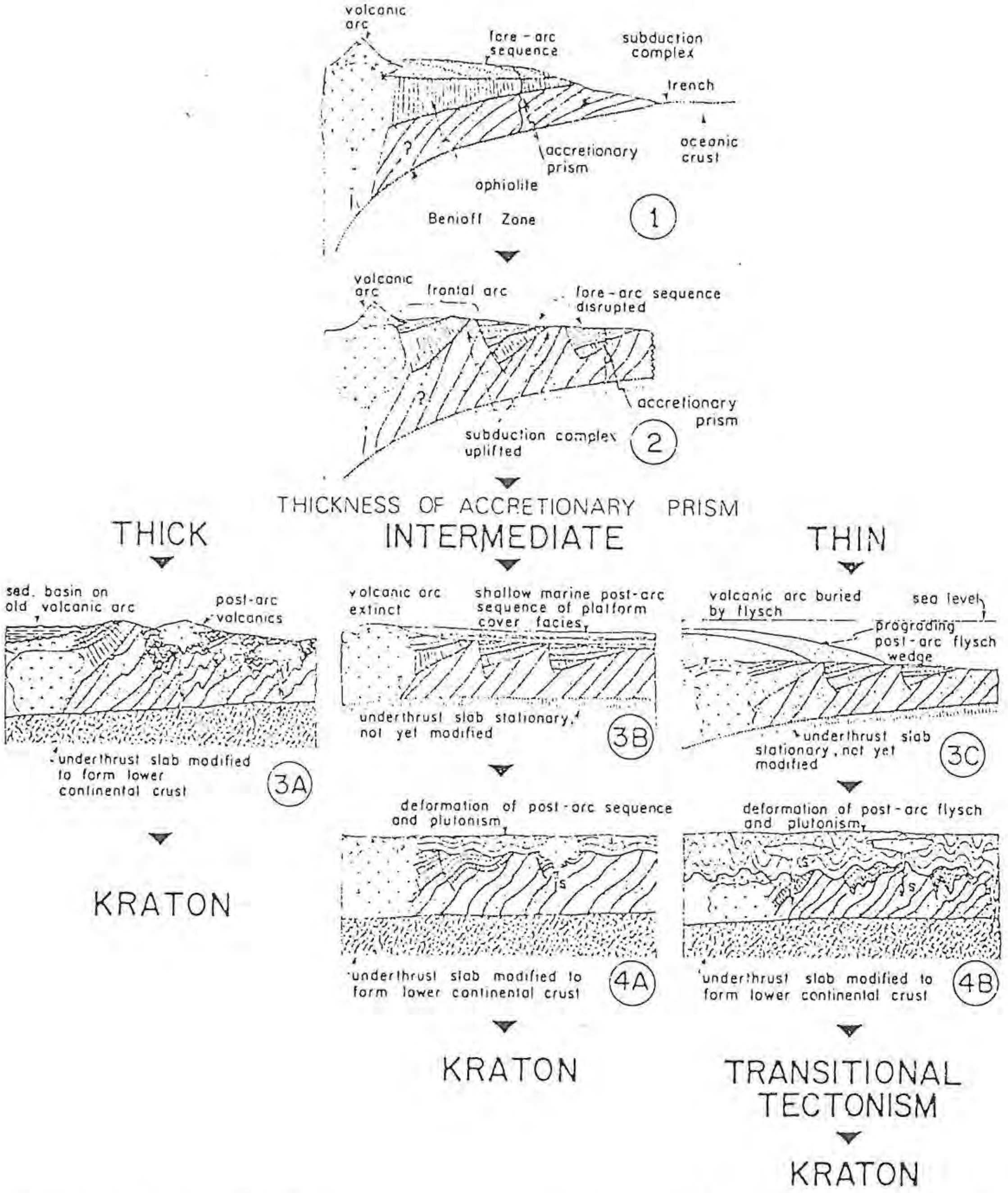


Figure 4.13 Model of the extended evolution of fore-arc regions and their associated volcanic arcs leading to cratonisation (Crook, 1980)

5.0 PRIMARY DEPOSITIONAL ENVIRONMENT OF SELECTED TURBIDITE-HOSTED GOLDFIEDS

It is proposed to review briefly the geology of a number of goldfields centred on turbidites, to analyse the relationship of gold-bearing quartz veins to hosting lithologies and to examine whether gold preconcentration in the sedimentary environment is of conceivable importance or not. Sedimentary rocks have the virtue of predictability; use of palaeocurrent directions, sequence analysis and observation of sedimentary structures make it possible to interpret the hydrodynamics and palaeogeography of an area. Familiarity with the whereabouts of source terrane places the exploration geologist to immediate advantage because he is then in a position to investigate all aspects of the weathering-transport-redeposition cycle acting upon hinterlands. Petrographic and geochemical studies may confirm the nature of the source rock material, maturity of the sediments and distance of transport. Gross facies changes within a sedimentary environment are an equally important consideration. For instance, gold mechanically concentrated in an off-shore alluvial-fluvial system, may be later catastrophically flushed into a turbidite fan with the development of a steep adjoining trough. Conceivably gold of the Witwatersrand basin may have ended up in turbidites had the basin eventually collapsed into a rapidly subsiding trough.

Sedimentary ore formation requires a prevailing set of physical-chemical conditions conducive for accumulation of metal in a particular environment without interruption. The association of many ore types with local or regional unconformities (diastems) in a volcanic or sedimentary environment is well documented (Anhaeusser and Button, 1976). The turbidity current process is punctuated by a series of such diastems represented at the tops (e division) of Bouma cycles. Development of diastems in a turbidite environment may be predicted according to sequences of fining- or coarsening-upward cycles (Refer Fig. 3.15). The e division of a Bouma cycle is commonly marked by accumulation of organic, pelagic and chemical precipitates (black shales, ferruginous shales and cherts) which may be conducive for gold concentration. Saager et al. (1982) noted remarkably higher concentrations of gold in ferruginous chemical sediments (oxide facies) and Algoma-type banded iron formations in South African greenstone belts. Boyle (1979) documented a number of examples showing the relatively high abundance of gold in pyritiferous black shales. Gold is either associated with fine-grained pyrite and pyrrhotite or with carbonaceous material as some type of organometallic compound or an adsorbed form. (A later chapter will discuss the role of diagenesis in further gold concentration).

a. Archaean Sedimentary Environments and Gold

Up to 60% of the world's cumulative gold production has been produced either directly from Archaean greenstone belts or indirectly from sedimentary basins whose hinterlands contained Archaean greenstones. Consensus of opinion favours that the gold itself originated from the greenstones (Goodwin, 1984).

Tilling et al. (1973) stated that gold deposits are mostly produced after structural deformation, granite intrusion and metamorphism and that apart from syngenetic stratabound occurrences in banded iron formation most gold is epigenetic. They concluded that gold may be relocated in any favourable lithological or structural setting anywhere in the greenstone pile and in neighbouring granites, excepting Archaean placer gold. It is well established that selected areas within greenstone belts are barren within respect to others, and for reasons which remain obscure some Archaean terranes are less prospective for gold than others. From an exploration point of view, it may'be argued that looking for favourable lithological and structural traps in such terrane is a wasted exercise. The ultimate source of gold in Archaean rocks is believed to be sulphur under-saturated mafic and ultramafic magmas (tholeiites and komatiites) which formed from parental mantle magmas enriched in precious metals (Keays, 1984). Mantle inhomogeneity is partly invoked for the regional distribution of gold through greenstone belts. Anhaeusser et al. (1975) showed that komatiites from the Barberton greenstone belt were not anomalous in gold but as Keays (1984) noted, relative abundances of rocks with different petrogenetic and fractionation histories are rather meaningless. Also komatiites which were initially enriched in gold may now have low levels since much of the gold may be lost after eruption onto the sea floor. Gold which is hydrothermally leached during seawater convection is either preserved within the volcano-sedimentary pile within chemical interflow sediments or intrusive dunites or lost to the oceans (Keays and Davison, 1976). Further redistribution of gold in the greenstone belt environment is restricted to the sedimentary cycle. Geochemical investigations on the range of gold concentration in Archaean rocks by Meyer and Saager (1984) demonstrated that Archaean epigenetic gold deposits may derive from pyritic and chemical clastic sediments.

Anhaeusser (1980) noted that Archaean sedimentary environments are very like those of modern (presumably Palaeozoic and younger) orogenic belts but on a reduced scale. The presence of a deep-to-shallow water clastic association is dominated by extensive, thick turbiditic fan or flysch-like sequences juxtaposed to subaerial alluvial fan facies. Sedimentary sequences of Barberton and Pilbara greenstone terranes are probably not likely to be favourable placer gold depositories unless the sediments are derived from some pre-3500Ma source terrane in which an earlier cycle of gold concentraton may have occurred.

Geological Setting of Some Gold Deposits

Barberton and Pilbara sedimentary sequences will be examined more closely (Figs. 5.1, 5.2). Fig Tree Group turbidites in the Barberton Mountainland

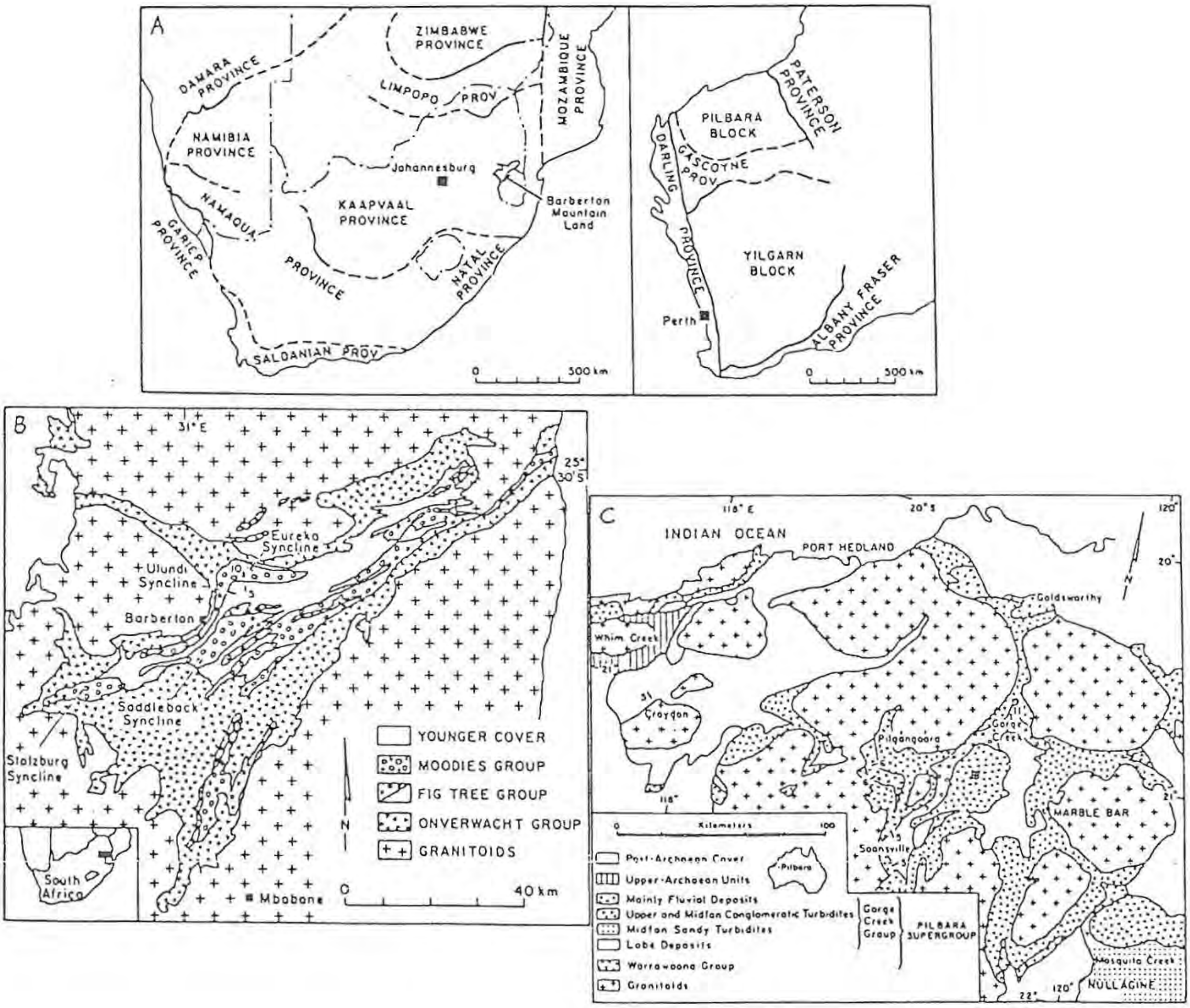


Figure 5.1 A. Tectonic provinces of Southern Africa and Western Australia showing location of the Barberton Mountainland and the Pilbara Block
B. Geological map of the Barberton Mountainland
C. Geological map of the Pilbara Block (Eriksson, 1983)

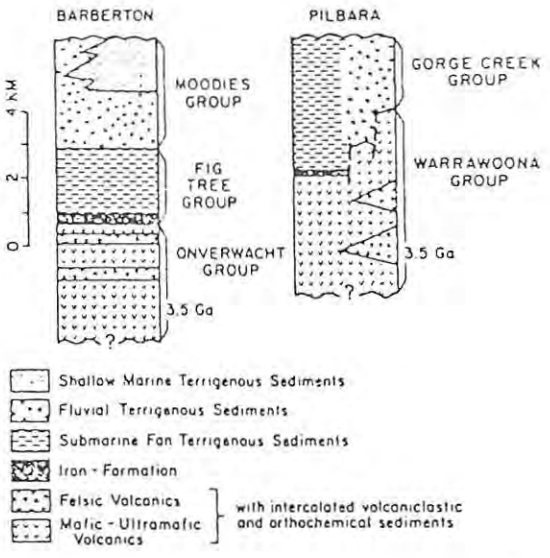


Figure 5.2 Simplified stratigraphic columns of the Barberton and Pilbara sequences (after Viljoen & Viljoen, 1970; Hickman, 1980) (Eriksson, 1983)

host gold in complex sulphide impregnation lodes at the Fairview goldmine. Auriferous lodes form a major cymoid loop close to the Fig Tree-Zwartkoppie (Onverwacht) contact (Fig. 5.3). Gold occurs within finely disseminated arsenopyrite and minor pyrite stringers and clots in black shales (Plates 5.1., 5.2)

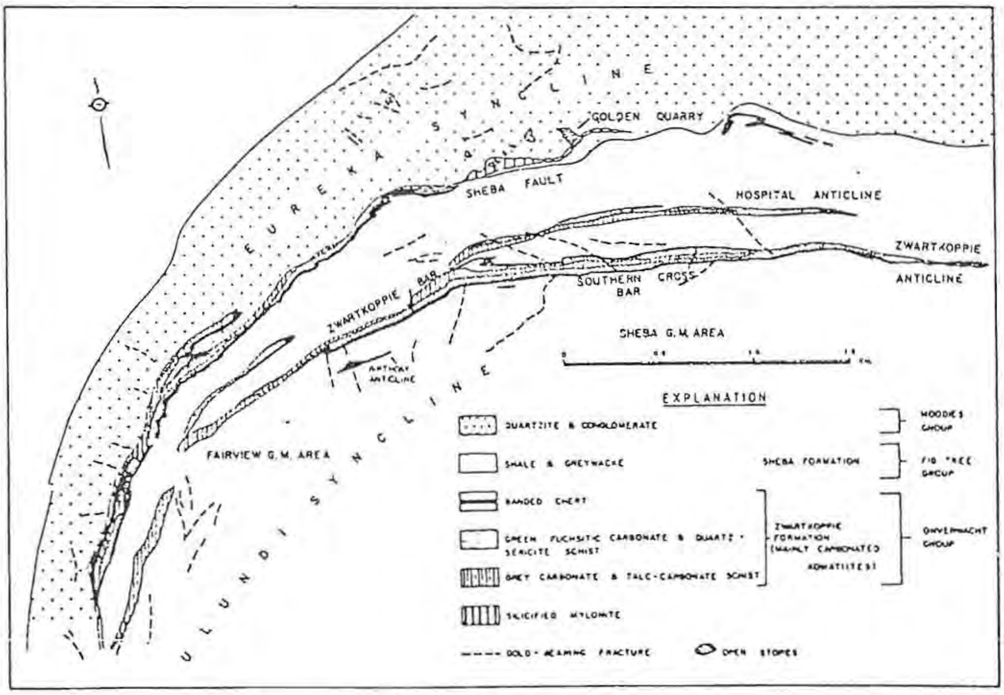


Figure 5.3 Regional geological setting of the Sheba and Fairview gold mines, Barberton greeenstone belt (after Anhaeusser, 1974; Wagener and Wiegand, in press; Wiggett et al., in press) (Viljoen, 1984)

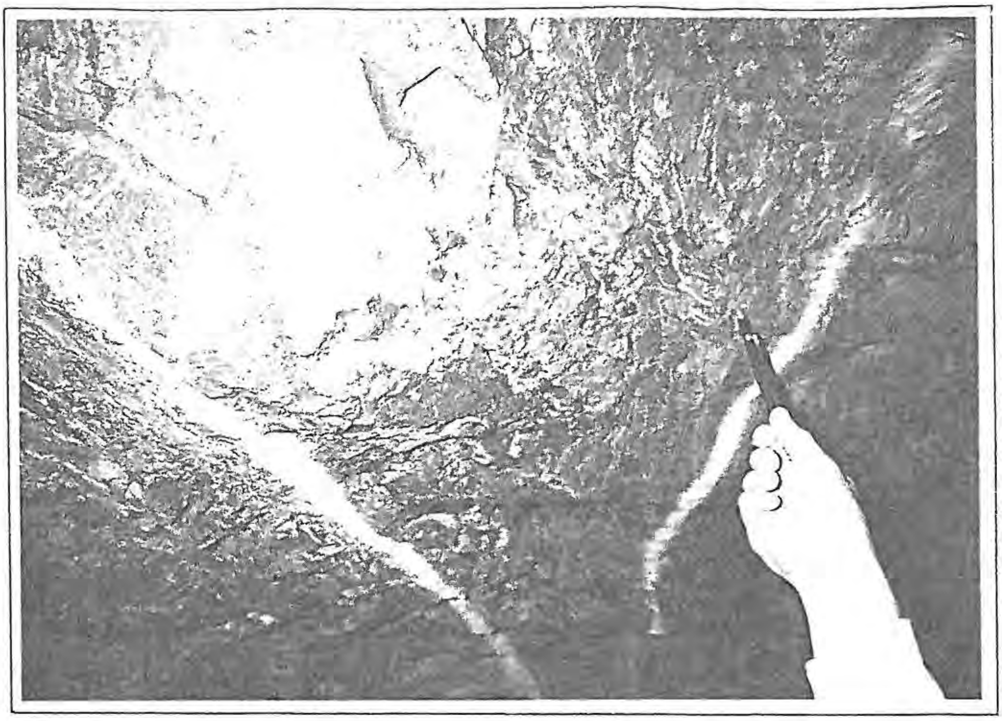


Plate 5.1 Stringers of arsenopyrite and minor pyrite forming gold-bearing complex sulphide impregnation lodes in black shales of the Figtree Group turbidite sequence at Fairview, Barberton Mountain Land.

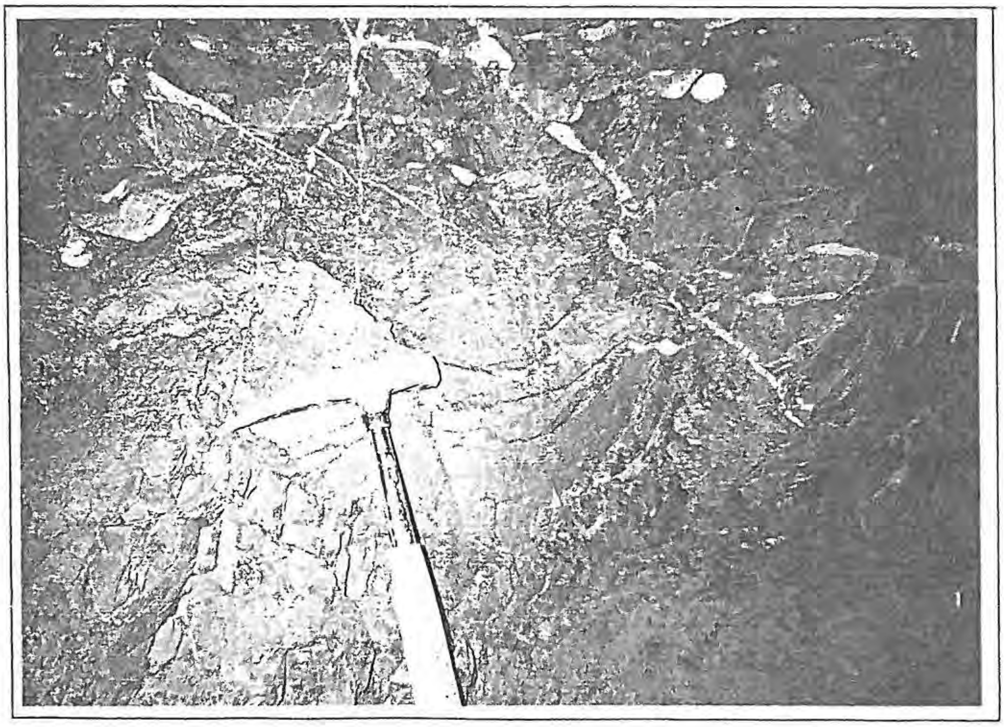
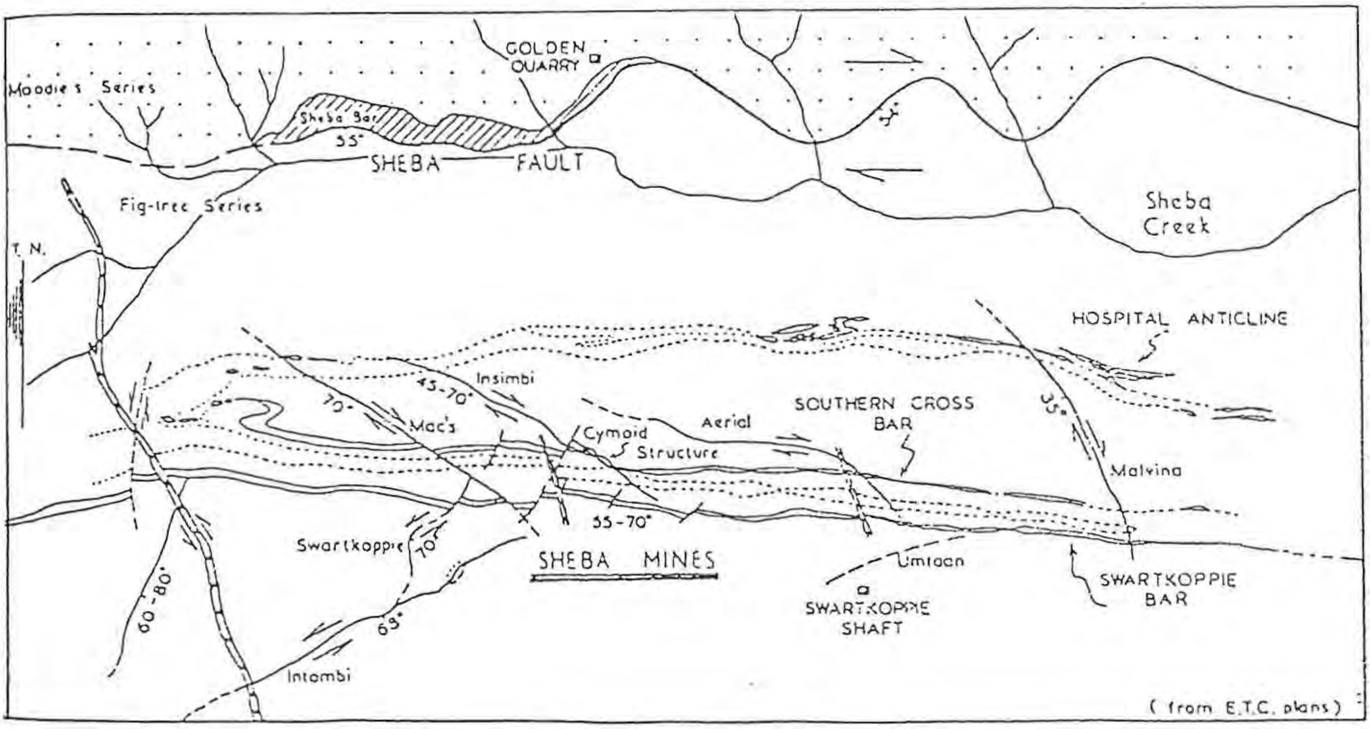


Plate 5.2 Auriferous pyritic clots impregnating black shales of the Figtree Group, Fairview

In the Sheba Mines area gold occurs in Figtree sediments of the Ulundi synclinorium within cymoid loops of complex sulphide type and quartz-filled fractures. Auriferous lodes and veins emanate from underlying cherts (Zwartkoppie, or Southern Cross Bar) and along the Sheba Fault between Figtree and Moodies Group sediments (Fig. 5.4). The Sheba Fault, marked by carbonate, hematite (after pyrite), chert, greenish talc and quartz-sericite schist has been equated with the capping Zwartkoppie iron formation (Plates 5.3, 5.4; Leeming, 1984; Ward, 1984).



(from E.T.C. plans)

Figure 5.4 Geology of the Sheba mines area showing principal structures (E.T.C. plan, 1984)

The Makonjwaan and Imperial gold mines lie within the lowermost portions of Fig Tree Group stratigraphy along the south-central flank of the Barberton Mountain Land. Mineralized units of both mines were described by Minnitt (1984) as stratiform and stratabound, with the Imperial overlying and separated from the Makonjwaan by approximately 400m of greywacke-shale beds. Two sedimentary cycles separate the mines, each approximately 200m thick and comprising greywacke-shale-chert and banded iron formation. The carbonate- and localized sulphide-facies banded iron formation hosts gold in association with pyrite, minor arsenopyrite and pyrrhotite.

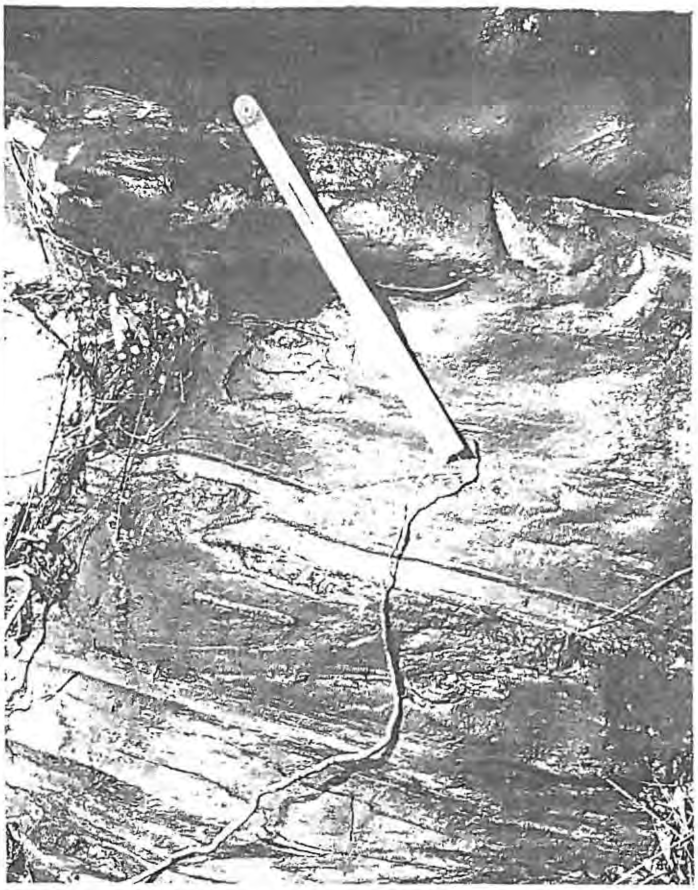


Plate 5.3 Fine ferruginous banded chert-shale unit of the upper Fig Tree Group turbidite sequence adjacent to Sheba Fault (South bank Sheba Creek)

Plate 5.4 Finely banded, contorted chert-talc-shale believed to represent anticlinal thrust slice of the Zwartkoppie banded iron formation

The Mosquito Creek Group sediments in the Pilbara host a number of narrow auriferous veins commonly confined to black shales between greywacke beds. Gold is associated with complex antimony and arsenic sulphides at Blue Spec, a mine which in the early 1970's closed due to gold extraction difficultites. The broadly synclinal basin is also host to a number of gold prospects situated stratigraphically on a siltstone- shale horizon (distal turbidite or basin plain facies) (Fig. 5.5).

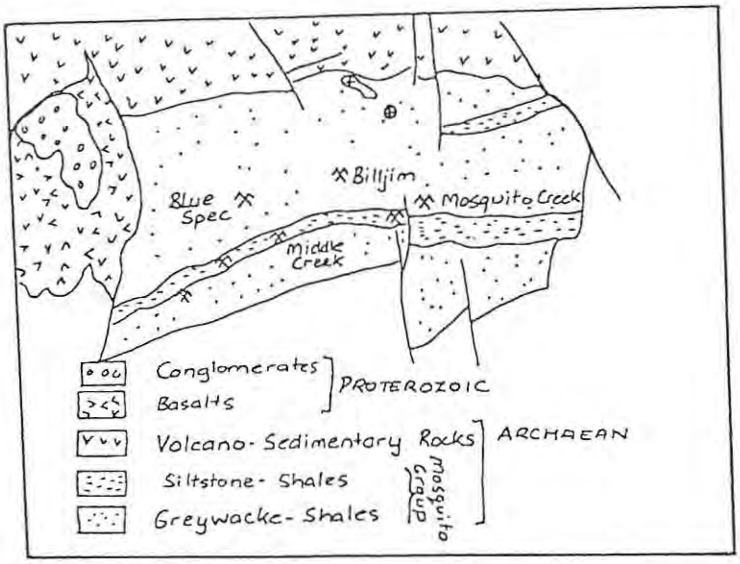


Figure 5.5 Geological sketch map showing gold occurrences in the Mosquito Creek Belt, Pilbara (adapted from Hickman, 1980)

Palaeogeographic Studies and Interpretation

Eriksson (1980a, b; 1981) recognized turbidite facies sediments in both the Fig Tree and Budjan Creek-Mosquito Creek Groups of the Barberton and Pilbara sequences respectively, which he interpreted in terms of existing submarine fan-slope models. Although palaeo-environmental analyses of Eriksson (1980a, b, 1981) were not specifically oriented to explain the gold mineralized environment, a number of observations are relevant and pertinant to the general geological setting:-

1) Proximal alluvial and distal turbidite facies occur in juxtaposition to the exclusion of shallow marine assemblages (Eriksson, 1980a), suggesting that Archaean depositories formed localized troughs proximal to source areas. Hence if gold occurrences were present in volcanic hinterlands it follows that eroded and redeposited detritus in turbidites may also host gold.

2) Palaeocurrent determinations indicated that Fig Tree sediments of Barberton derived south of the Ulundi and Stolzburg synclines from source terrane comprising dominantly Onverwacht Group ultramafic and mafic volcanics. Geochemically, source terrane changed from mafic to silicic due to the progressive stripping of Onverwacht stratigrahy (Eriksson, 1980b). In the east Pilbara, sediments of the Mosquito Group derived from the north and east, and clasts suggest reworking of volcanics, cherts and banded iron formation of the Warrawoona Group. Eriksson (1981) erected a palaeogeographic model for the east Pilbara which demonstrated rapid filling of early grabens by braided-river sediments which were then supplied to the trough. Submarine fans prograded across basal banded iron formations, which apparently developed on the floor of the troughs in response to waning volcanism (Fig. 5.6). Either gold was mechanically reworked from volcanic source terrane on the alluvial braid plain prior to redeposition on the turbidite fan, or gold-enriched fluids from late stage metasomatism were incorporated into the sediment pile during deposition.

3) Using vertical sequence analysis on Barberton sediments Eriksson (1980) showed that mid-fan turbidites of the Figtree Group with complete Bouma cycles (a to e) were randomly interbedded, signifying channel and interchannel deposition. Slope deposits of a prograding fan overlying mid-fan sediments were characterized by thick shale-banded iron formation-chert sequences with abundant soft sediment folding and occasional greywacke interbeds. These passed stratigraphically upward into massive greywackes with intercalated channel fill and matrix-supported conglomerates of the feeder channel, and eventually graded to fluvial conglomerates of the Moodies Group.

Cyclic deposition in both Moodies and Fig Tree Group as well as the Pilbara sequences is commonly marked by ferruginous chert and jasper. Eriksson (1983) recently noted subordinate but common intercalations of iron formation within upper greenstone ferruginous clastic sequences in a number of palaeoenvironmental settings. Iron formation was not only found at the base of progradational off-shore shelf-beach sequences and in lacustrine deposits intercalated within thick braided alluvial sequences, but was also well developed in turbiditic sequences. Particular settings in turbidites where iron formation occurred include:-

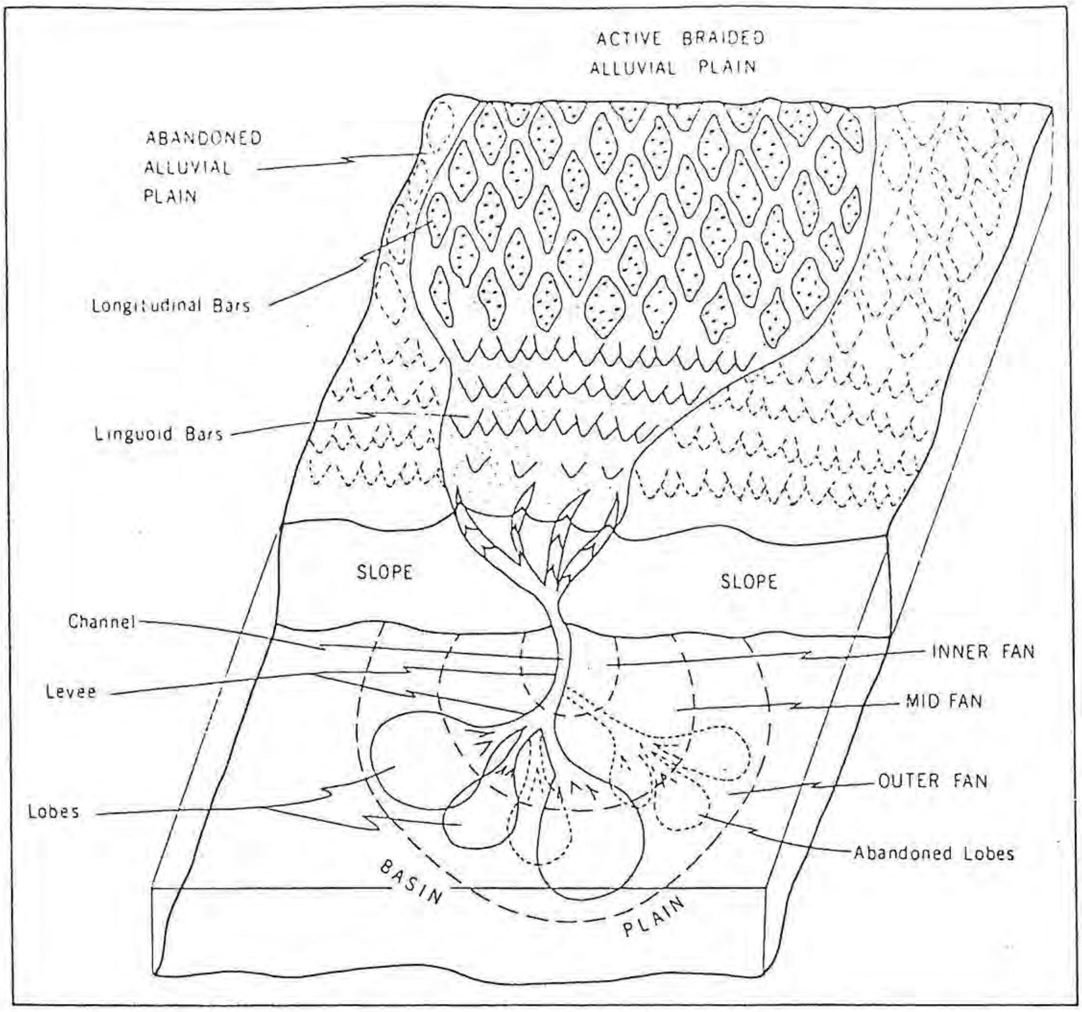


Figure 5.6 Palaeogeographic model showing the contemporaneous development of braided alluvial and submarine-fan depositional environments (Eriksson, 1981)

1) At the base of prograding submarine fan sequences (Fig. 5.7)
2) Within interchannel mudstones enclosing inner and mid-fan channel deposits (Fig. 5.8)
3) Capping Bouma turbidite beds (Fig. 5.7)
4) Intercalated within outer fan and basin plain mudstones (Fig. 5.7)

Alternate Origin for Banded Iron Formation - Discussion

The origin of iron formation or so called exhalative facies in the Archaean has received much attention since it was recognized that gold in banded iron formation possibly represented a significant protore for subsequent enrichment by deformation and metamorphic processes. Fripp (1976) postulated that active fumerolic geothermal brines involving convection of seawater driven by a subvolcanic heat source were responsible for generating banded iron formation; De Wit et al. (1983) suggested that sedimentation overlapped with exhalation of late stage,

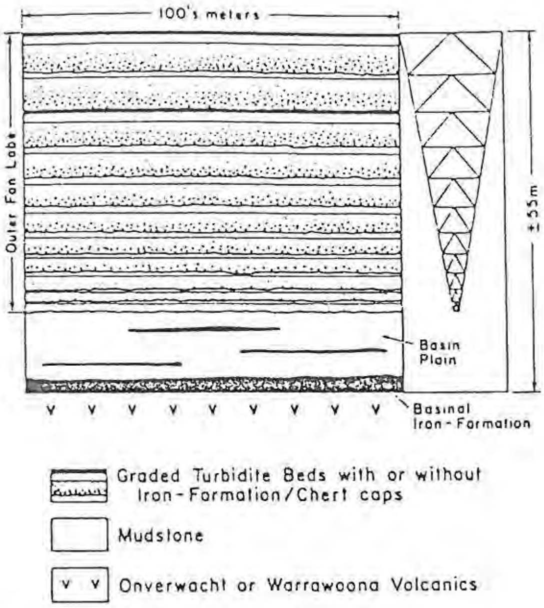


Figure 5.7: Idealised cross-section of outer fan lobe-basin plain from the Soansville in the Pilbara Block, showing iron-formations of basinal and basin-plain origin, as well as capping graded turbidite beds (Eriksson, 1983)

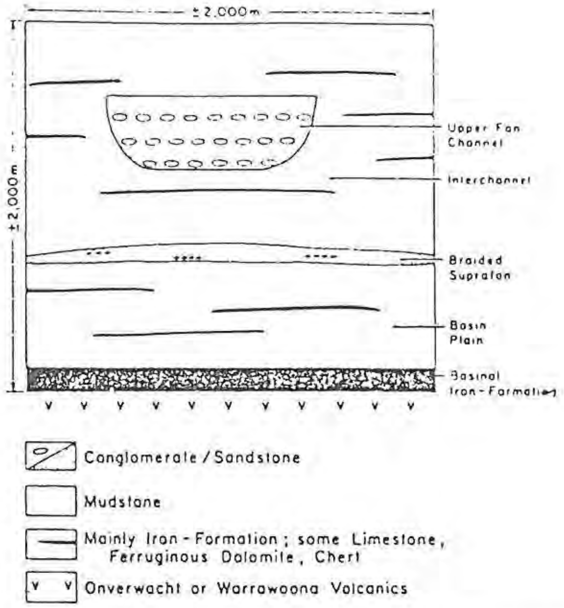


Figure 5.8: Idealised cross-section of braided suprafan and upper fan-channel, coarse, terrigenous sediments and their relationship to interchannel and basin plain mudstones and orthochannel sediments from the Pilgangoora Syncline, Pilbara Block (Eriksson, 1983)

pervasive metasomatic products which were related to widespread hydrothermal activity and driven by heat sources from igneous intrusions; Goodwin (1984) proposed that exhalative chert and banded iron formation were essentially volcanogenic representing the culmination of fractional crystallization processes; Kerrich and Fyfe (1981) suggested that metamorphic fluids were exhaled at the sediment-seawater interface. All processes were interpreted as significant for promoting gold enrichment in essentially a primary geological environment. Postulated origins for Algoma-type banded iron formation and Archaean chemical sediments invariably invoke endogenous volcanic plutonic sources. Eriksson (1983) questioned the validity of these models when iron formation and orthochemical sediments may also define diastems in the deepest water facies between terrigenous influx over large areas e.g. 100 x 150km in the Pilbara, implying a substantial body of water. Genetic models for the predominantly sediment-hosted Superior-type iron formation of the Proterozoic are also inadequate for turbidite-hosted iron formation. Lacustrine, restricted basin or evaporitic models generally involve upwelling of reduced Fe^{2+} to shallow O_2 rich waters of a stratified hydrosphere, with seasonal temperature-density stratification (Gole and Klein, 1981).

Eriksson (1983) proposed a model for turbidite-hosted banded iron formation involving direct precipitation of Fe and SiO_2 from concentrated ambient hydrosphere according to small fluctuations caused by photosynthesis of algae floating at or near the surface. He also suggested that SiO_2 was concentrated up to 100ppm (compared to 10ppm) in Precambrian hydrosphere in addition to concentrated Fe^{2+}. If the observation by Keays and Davison (1976) that gold in sulphur-undersaturated tholeiitic and komatiitic lavas was partly lost to seawater on eruption due to high temperature fluid interaction, it may be suggested that Archaean seawater became more concentrated in gold near extrusive centres. Gold may precipitate as pelagic fallout with fine aquagene tuffs either between lava flows or terrigenous influx. This proposal is consistent with the observation that sediments associated with oceanic ridges and rises contain higher than average amounts of gold (Boyle, 1979). Alternatively, gold may be absorbed by plankton which on their death are sedimented in clays and other marine sediments. With the onset of deep-water sedimentation in the volcano-sedimentary environment of an Archaean greenstone belt, gold may continue to accumulate, albeit within a somewhat more predictable environment.

The importance of sedimentary breaks with respect to gold mineralization has been emphasized by Viljoen (1984) and Ward (1984). Siliceous, carbonaceous, ferruginous dolomitic and calcareous precipitates of the chemical and biogenic Zwartkoppie Formation were identified by Ward (1984) within a number of narrow inliers along a series of thrusted anticlines including the Consort Contact and the Moodies, Sheba, Zwartkoppie, Barbrook, Saddleback and Inyoka Faults (Plate 5.4). Eriksson (1983) interpreted this exhalative as a basinal-type iron formation. In the Pilbara the iron formation attains a thickness of tens of metres and an areal extent of thousands of square kilometres and in the Barberton Mountainland is as thick but less extensive areally. The basinal deposit accumulated on the sea floor prior to the first influx of terrigenous sediment and subsequent submarine fan progradation. Eriksson (1980) identified 15cm-thick cycles comprising tuff-hematite-jasper in the Barberton banded iron formation in which jasper layers commonly display evidence of soft sediment deformation. Preferential affinity of gold mineralization for carbonate- and sulphide-facies banded iron formation has been well documented. (Sawkins and Rye, 1974; Minnitt, 1984; Phillips et al., 1984). Stable isotope studies may demonstrate more conclusively whether stratigraphically confined epigenetic vein-hosted gold and sulphides were introduced post-deposition and involved with sulphidization of iron (Phillips et al., 1984) or simply remobilized in situ (Sawkins and Rye, 1974).

b. Proterozoic Sedimentary Environments and Gold

The Archaean represents one of the most significant periods in the geological time record for concentrating gold. It follows that reworking of Archaean terrane should be significant for concentrating gold. The Witwatersrand (2800-2500Ma) may be regarded as exceptional because basin formation occurred prior to oxygenation of the atmosphere at around 2300Ma. Anoxic hydrospheric conditions were regarded as significant for promoting gold enrichment particularly in association with the Carbon Leader.

The Proterozoic, generally represents one of the least important periods for concentrating gold and perhaps reflects the relatively small proportion of Archaean greenstone belts (10%) occupying shield areas. In other words, reworking Archaean terrane en masse has the effect of diluting and dispersing gold with eroded material derived from the 90% remaining non-auriferous granite-gneiss terrane. The depositional environment was also perhaps less conducive for concentrating gold. Windley (1984) differentiated three main Proterozoic environments on the basis of stratigraphic and geotectonic setting:-

1) Quartzite-shale-carbonate assemblages, which dominate the Proterozoic reflect the predominance of a stable rifting environment. Some 60% of Proterozoic terrane is represented by thick (up to 10km) clastic-biogenic accumulations along passive continental margins. Eroded granite-gneiss shields were reworked to massive cross-bedded sandstones which, in the Early Proterozoic were interbedded with red beds, carbonate banks, chert and banded iron formation. Rifted continental margins continued through to the Middle and Late Proterozoic when typically successions of shallow-marine quartzites and sandstones, platform carbonates, pre-flysch deep water laminated fine-grained mudstones, flysch and molasse accumulated.

2) Calc-alkaline volcanic-greywacke successions, which characterize up to 20% of Proterozoic terrane are directly comparable with Archaean greenstone belts. Windley (1984) favoured a magmatic arc-related tectonic setting for these Proterozoic greenstone belt successions.

3) Bimodal volcanic-quartzite-arkose assemblages, which accumulated in 5-10km successions of some 20% of the Proterozoic. Intracratonic rift and aulacogen-type tectonic settings influenced the mixed subaqueous and subaerial depositional environment in which bimodal basalt-rhyolite volcanism alternated with immature clastic sedimentation (arkose, feldspathic quartzite, conglomerates, occasional iron formation, carbonate, shales and red beds).

The latter environment is particularly noted for accumulation of giant massive sulphide orebodies, while the former two are better known for gold mineralization either partly if not wholly hosted by quartz veins in turbidites.

An Early Proterozoic Greenstone Belt

The Birimian system of Ghana represents the type province of the Early Proterozoic Eburnian tectonic cycle, and hosts important vein and lode-type gold in predominantly turbidites.

The slightly younger Tarkwaian system also hosts gold in grits, quartzites and pebble conglomerates of the Banket Formation, and is believed to represent reworked rocks of the Birimian system (Fig. 5.9).

The geotectonic setting and regional geology of Ghana is somewhat disputed between Anglophone and Francophane schools of thought (Hastings, 1982) and would appear to require a great deal of geological investigation, dating and regional synthesis before the Eburnian tectonic cycle is at all clear. Available English literature recognized the Lower Birimian, comprising primarily phyllites and greywackes with tuffs becoming important towards the contact with the Upper Birimian, a volcano-sedimentary series of metamorphosed basalts, andesites,. and rhyolites with intercalated phyllites and greywackes. The Tarkwaian clastic succession is believed to be a derivative of the Birimian (Table 5.1). Contrastingly the French considered the Tarkwaian and Lower Birimian to be undifferentiated members of the predominantly sedimentary Birimian Supergroup which they consider to be younger than the volcano-sedimentary series of the Upper Birimian. Rocks of the volcano-sedimentary series are believed to represent localized emplacement along graben or block fractures, and the Birimian Supergroup sediments were derived from the volcano-sedimentary series.

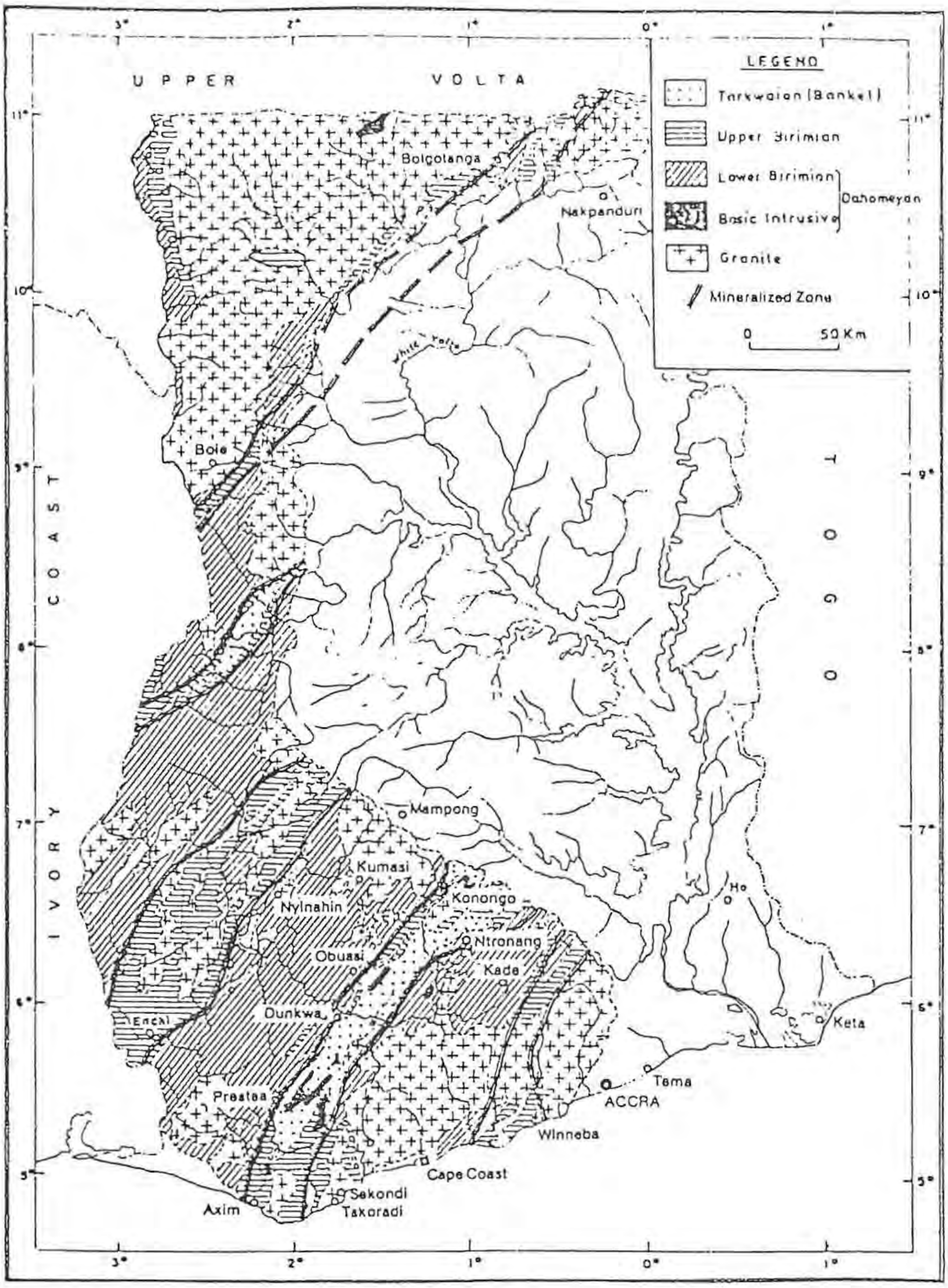


Figure 5.9 Gold belts within the Birimian System, Ghana (Kesse, 1984)

Table 5.1 Sedimentary succession of the Birimian and Tarkwaian systems in the Tarkwaian belt, Ghana (Kesse, 1984)

System	Formation	Thickness (metres)	Composite lithology
Tarkwaian	Huni	1370	Phyllites, sandstones
	Tarkwa	120 - 400	Phyllites and quartzites
	Banket	120 - 600	Grits, quartzites, pebble-conglomerates
	Kawere	250 - 700	Quartzites, grits and phyllites
Birimian	Upper	10 000 - 15 000	Metamorphosed lavas, pyroclastic rocks, hypabyssal intrusives, phyllites and greywackes
	Lower		Phyllites, schists, tuffs and greywackes

The French interpretation compares with the classic model of Archaean greenstone belt evolution, and other known Early Proterozoic greenstone belts with mafic to differentiated volcanics volcanoclastics flysch shallow water clastics (compare Barberton stratigraphy). The most important form of vein and lode-type gold occurs either near the contacts between the Lower and Upper Birimian rocks or within Birimian rocks. Major gold-bearing belts occur near the contact as shown in Figure 5.10 and include the Ashanti goldfields along the Akanko-Presta-Begaso-Obuasi-Obuous-Konongo belt (Fig. 5.9). Quartz veins range from a fraction of a metre to 30m or more in width and extend for a few metres to several thousand metres in length. Some veins are isoclinally folded within the Birimian rocks but more frequently they occur in shear zones where they are also associated with carbonaceous phyllites and gouge. Gold contents are high in the orebodies but patchy, ranging from nil to 34g/t but very high grades (170g/t to 850g/t) are common in the rich Obuasi and Konongo areas (Kesse, 1984).

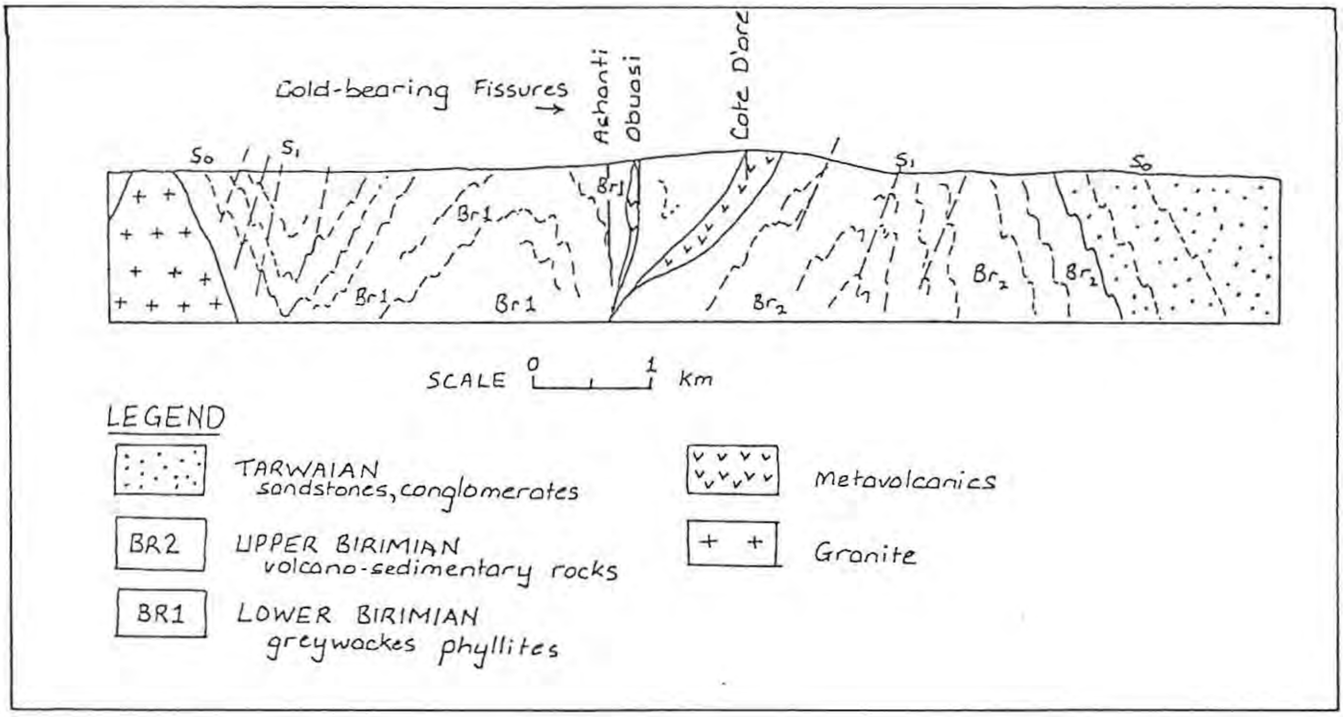


Figure 5.10 Section across the Obuasi Gold Belt (Amanor et al., 1977)

Sulphide ores in widespread Birimian tuffaceous phyllites are also an important source of gold. Horizons up to 30m in thickness occur in specific stratigraphic settings.

Available documentation on the Ashanti goldfields emphasizes the structural aspects of auriferous veins mined at Ashanti unfortunately to the wholesale exclusion of information on the host rock and regional geological environment.

Pre-existing structures related to F_1 compression and post-folding FI appear to be largely responsible for the control and trapping of mineralizing solutions and producing ore-shoot geometry. The few attempts at resolving the origin of the mineralizing solutions have suggested:-

1) a spatial and therefore genetic relationship with granites (situated 5km west). The granite was rejected as the source of mineralization on grounds that emplacement was prior to F_1 deformation;

2) desilication of wall rocks adjacent to reefs for up to 8m, and a relative increase in carbonate and sericite. This lateral secretion model assumed that the wall rocks were relatively gold-enriched prior to deformation. Carbonaceous matter often present in gold-bearing fissures is believed to be derived from the sediments but apparently shows no sharply defined influence on the deposition of gold;

3) a regional metamorphic diffusive origin in which circulating ground waters of regional metamorphic origin migrated towards areas of low pressure. This model was queried because pyrite which is present in country rocks is generally absent with other sulphides in the reefs;

4) a deep seated origin as suggested by an open plumbing system of ore shoots which have continuity at depth as low grade channels.

Amanor et al. (1977) concluded that without isotope analysis, geothermometry and whole rock analysis used in mass transfer reactions, models for the origins of mineralizing solutions must remain speculative. However, some points are worth noting here.

Auriferous lodes and quartz reefs are associated with and occur in tightly folded Lower Birimian phyllites, metagreywackes and tuffs close to an arbitrary contact with metamorphosed and metasomatically altered intermediate to basic Upper Birimian volcanics (Fig. 5.10) (Amanor et al., 1977). The ill-defined contact between the Upper and Lower Birimian exhibits interfingering relationships between the submarine, moderately deep, turbiditic sediments and subaerially deposited lavas, agglomerates, tuffs and tuffaceous sediments. The contact may actually represent a concomittent facies change.

Metasomatically altered volcanics were leached of their gold which drained into adjoining deep sea troughs. Unless conditions are favourable, hydrothermal fluids of the late stage geothermal systems are unlikely to redeposit all of the leached gold within the convection system because it would require sustained conditions for precipitation (Keays, 1984). Precipitation of epithermal gold would only occur intermittently in response to

a) boiling of geothermal solutions
b) a change in physico-chemical environment (Rossiter, 1984)

It is proposed that leached gold of the Birimian volcanics may have discharged into flanking steep rift troughs characterized by turbidity currents. Turbidites have the redeeming feature of preservation because each turbidite bed is deposited below the storm wave base. In addition, the passing of each turbidity current is marked by a hiatus during which accumulation of fine tuffaceous ash (often gold enriched, Boyle, 1979) and organics may occur in locally reducing bottom conditions. Scavenging and preferential concentration of gold from locally enriched discharge waters by organics and sulphur is proposed.

The preponderance of argillaceous and fine to intermediate arenaceous rocks represented by black phyllites, meta-siltstones, meta-greywackes, tuffaceous sediments and ash tuffs in the Lower Birimian give way to auriferous shear zones within sericite schist, chlorite schist and carbonaceous schist near the contact with Upper Birimian volcanics. The localized graben setting of volcanic formations is clearly more feasible both in a structural and stratigraphic sense with the abundance of gold localized near turbidite-volcanic contacts on a regional scale.

The presence of an open plumbing system in the Ashanti goldfields may favour a deep seated metamorphogenic origin, which will be discussed in the following chapter.

Passive Continental Margins

Passive continental margins represent the most important geotectonic setting of the Proterozoic when Superior-type banded iron formation, carbonate and carbonaceous shales accumulated in restricted or protected marginal shelf environments. These formations are mostly poorly mineralized with respect to gold, and whereas Algoma-type banded iron formation and ferruginous cherts of the Archaean are relatively gold-enriched, Superior-type are not. Is the presence of primitive magmas critical for the introduction of gold into the crust and that of consuming plate margins to recycle, fractionate and concentrate gold even further? The problems of relating gold abundance to igneous rocks are discussed more fully by Boyle (1979). Generally gold exhibits a positive correlation with sulphur and the presence of pyrite, chalcopyrite and pyrrhotite in igneous rocks. Shallow depositional environments are well oxygenated and reworking caused by regression and transgression were obviously less conducive for localizing gold by either chemical or physical means.

Two important gold deposits which feature in the Proterozoic, include the Pilgrims Rest-Sabie-Lydenburg vein deposits of the eastern Transvaal and the Telfer deposit of the Paterson Province in Western Australia. Pilgrims Rest is strictly a shelf-facies hosted vein deposit whereas auriferous veins of Telfer are hosted in marginal turbidite facies bordering on a predominantly clastic shelf environment. The deposits are of interest in this discussion because

1) both are relatively undeformed and well preserved
2) auriferous veins are stratabound
3) protores to vein formation have been identified in both environments
4) neither deposit is directly associated with volcanism
5) sedimentary environments are developed on the margins of older cratonic shield areas.

Pilgrims Rest produced a total of 136 tonnes of gold from extensive stratiform quartz reefs within the Malmani Dolomite of the 2100-2300Ma Transvaal Supergroup. Auriferous quartz bodies were localized on planes of infrastratal movement (bedding plane thrust faults) along thin shale bands in arenite and carbonate units, and within arenite-argillite alternations along lithological contacts (Button, 1976). Extending for up to 10km along strike principal quartz sheets were enriched along the crests of gentle anticlinal warps. Minnitt et al. (1973) noted the intimate association of mineralized veins with carbonaceous shale bands in the dolomite. The discovery of a significantly enriched (up to 90ppb Au) carbonaceous siltstone-shale horizon near the Malmani-Black Reef transition suggested that such sediments may represent protore for the Pilgrims Rest gold-quartz reefs. Gold occurs as submicroscopic disseminations in the shale where it is adsorbed selectively by a nucleation process onto surfaces of illitic clays, carbonaceous matter, iron sulphides and quartz. The ultimate source of gold in the sediments remains speculative with the lack of isotope, fluid inclusion and whole rock chemical analyses.

Stratabound gold deposits at Telfer occur within two carbonate-bearing siltstone members in a thick sequence of arenites, siltstones, mudstones and carbonates comprising the Proterozoic Yeneena Group (Fig. 5.11) (Turner, 1980). The ore-hosting Telfer Formation comprises alternating pyritic sandstones and shales with a set of sedimentary structures typical of turbidite facies (Table 5.2; Eriksson, pers comm., 1980). The Yeneena Group is believed to be a facies equivalent of the Bangemall Group, comprising predominantly shallow water cross-bedded fine to coarse-grained quartz sandstone with minor carbonates (Goode and Hall, 1981; Goode, 1981). Intercalating siltstones and shales with pyritic sediments to the north-west of the Bangemall Basin, and the occurrence of less mature feldspathic sandstones at Constance Headland suggests that shallow basin deposition deepened to a localized N-W trending trough near the Rudall Inlier (Fig. 5.11).

Ore reserves at Telfer total 4,3M tonnes grading 10g/tonne. The best developed ore horizon, the Middle Vale Reef (MVR) occurs in the lower siltstone member which outcrops around an elliptical pericline 3km long, known as the Main Dome (Fig. 5.12). Further reefs (E1 and E2) of the upper siltstone member, are separated from the MVR in the hangingwall by a number of Bouma cycles (pers. comm. Eriksson, 1980) and occur discontinuously around the Main Dome and a subsidiary pericline, the West Dome (Turner, 1980).

Gold occurs in quartz-limonite beds up to 1,5m thick and most of the mineable ore occurs in the oxidized zone. Although visible gold is fairly common, most gold particles are less than 20 microns across and

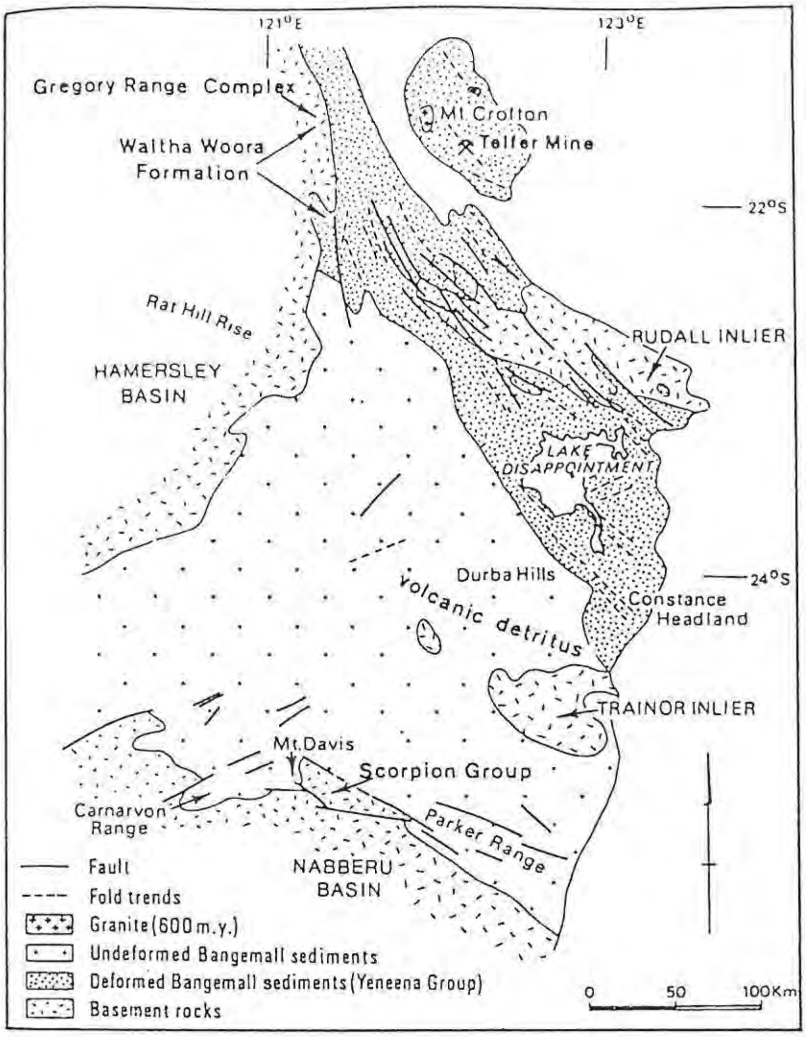


Figure 5.11 Generalised geological map of the eastern Bangemall basin, Western Australia (Goode and Hall, 1981)

Table 5.2 Stratigraphy of the Yeeneena Group (after Williams et al., 1976; Chin et al., 1979 and others) (Goode, 1981)

Formation	Approximate thickness (m)	Lithology
Kaliranu Formation	350+	silty dolomite, shale
Wilki Quartzite	1000	massive quartz sandstone
Telfer Formation	c. 500	interbedded pyritic quartz sandstone, shale
Malu Quartzite	0—750	massive quartz sandstone
Isdell Formation	>1000?	dolomite, dolomitic shale with minor sandstone, siltstone, conglomerate
Choorun Formation	2000	sandstone, micaceous siltstone, quartz pebble conglomerate, shaly dolomite;
Broadhurst Formation	500—1000?	micaceous siltstone, mudstone, shale, graphitic shale, fine sandstone
—Unconformity—		
Coolbro Sandstone	up to 4000	cross-bedded quartz sandstone with basal conglomerate

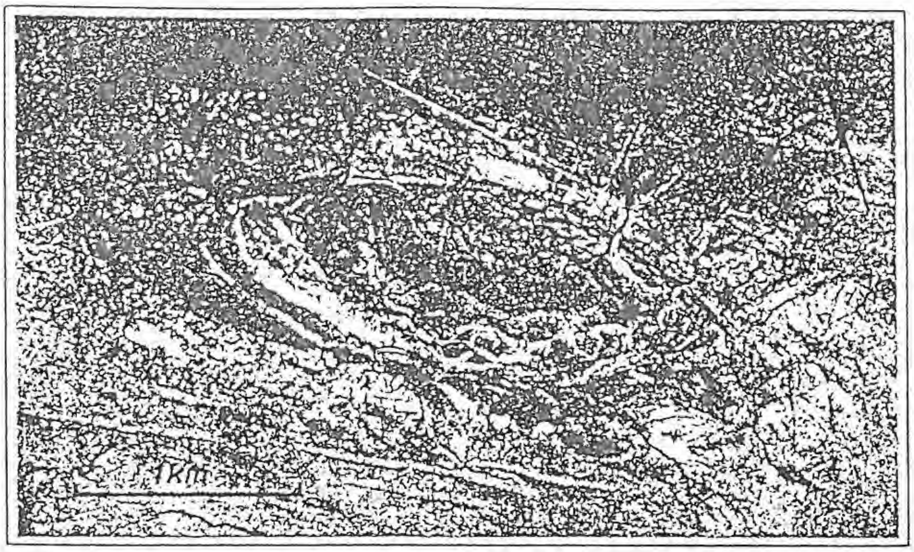


Figure 5.12 Aerial photograph of the Telfer Dome showing the alteration between sandstone and shale units. Road system (pre-development) within the dome outlines the approximate location of the stratabound gold mineralization (Goode, 1981)

occur in limonitic boxworks after pyrite. At depth the grade of mineralization decreases below about 100m (depth of oxidation) where the MVR grades to massive bedded pyrite, pyritic laminae and disseminated pyrite in a greenish, kaolinitic siltstone with pinkish chert. Ores are enriched in Cu, Co, As, Ag, Bi and Mo in addition to Au. The auriferous vein deposits, which occur in a domal setting resemble saddle reefs (Boyle, 1979).

Turner (1980) postulated that the deposits may have syngenetic origins with precipitation at the sedimentary surface from metal-rich brines. Alternatively granite dated at 600Ma, which intruded the sediments some 25km west of the deposits may be responsible for migrating hydrothermal solutions which formed epigenetic replacement deposits. The origin of the Telfer deposit is currently being researched.

A few points are worth noting:-

1) Telfer is situated along a major lineament, the Paterson-Musgrave trend, which is apparent on Australian geological and geophysical maps, aerial photographs and satellite imagery (Austin and Williams, 1978). Deep seated faulting may tap brines related to dewatering of higher grade metamorphism at depth, during deposition of the Yeneena Group.

2) Metamorphism increases to greenschist facies towards the Paterson Province. The rest of the Bangemall Basin is characterized by low grade metamorphism.

3) Sandstones of the McFadden Sandstone, Bangemall Group, which may correlate with the Wilki Quartzite overlying the Telfer Formation exhibit contradictory and unusual features: well rounded, well sorted quartz grains are commonly cemented by matrix clay which predominates over authigenic quartz cement. Goode and Hall (1981) proposed that the clay was supplied by contemporaneous addition of large quantities of volcanic ash (airborne and reworked aqueous). The volcanic hypothesis is supported by the presence of tuff horizons found to the north and south of the Trainor Inlier.

5) Presence of pyrite and turbidite structures in the Telfer Formation suggests below wave base, marginal trough-like deposition in relatively anoxic conditions. Preservation of auriferous chemical sediments, fine silts, and volcanic ash (?) betweeen sandstones may be promoted by the turbidite environment.

6) The auriferous, pyritiferous, kaolinitic and cherty siltstone, to which the MVR grades at depth may represent a diagenetic formation. The role of diagenesis in ore formation is discussed in the following chapter.

7) The high grade gold mineralization in quartz-limonite reefs encountered above the oxidation level is almost certainly caused by processes of supergene enrichment acting upon essentially a protore sedimentary formation.

C. Goldfields of Palaeozoic Geosynclines

The Palaeozoic represents the second most important gold concentrating period outside the Archaean. Oxygen levels had increased, life forms in the oceans proliferated and tectonic regimes stabilized to plate motions much as we know today.

Primitive mantle magmas are generated at oceanic spreading centres, forming oceanic plates which accumulate pelagics, turbidites and basin plain deposits. Complex interactions between oceanic and continental plates takes place during subduction of oceanic lithosphere comprising primitive mantle material (mid-ocean ridge basalts) and ocean basin sediments. Continental accretion culminates in processes of magma generation often with crustal materials being recycled, metamorphism and deformation.

Over relatively short periods of geological time (200Ma) substantial thicknesses of sediments accumulated during accretionary tectonic processes in subduction-related regimes. Mechanics of such sedimentation are now much better understood in terms of plate tectonics. However unravelling, the tectonic history and development of Palaeozoic geosynclines is not simple. Identifying elements of back-arc-arc-forearc regimes in their original context (pre-metamorphism, deformation, plutonism) though palaeogeographic reconstruction is perhaps one of the most effective measures for establishing crustal evolution in the Palaeozoic. Its usefulness may also extend to metallogeny.

Volumetrically the gold produced from the Central Victorian goldfields is comparable with one of the goldfields of the Witwatersrand, and rates with the Muruntau deposits of Palaeozoic age of the U.S.S.R. The Central Victorian goldfields were hosted in turbidites of the Tasman geosyncline in Eastern Australia while, similarly host rocks of the Palaeozoic Murunteau deposit are Palaeozoic flyschoid sequences developed in the Hercynian geosynclinal belt of the Southern Tyan-'Shan' (Boyle, 1979; Borodaevskaya and Rozhkov, 1977). The Reefton goldfield of New Zealand represented the most productive of auriferous vein deposits hosted in turbidites of the Western Sedimentary Belt in the South Island (Henley et al., 1976).

In all cases gold was hosted in quartz veins with minor sulphides, mainly pyrite and arsenopyrite. Previously thought to be granite-related, isotopic studies have since shown that the veins are of metamorphic hydrothermal origin. Henley et al. (1976) and Glasson and Keays (1978) separately investigated derivation, transport and concentration of gold during metamorphism and/or deformation. Both acknowledged the necessity for comparatively enriched source rocks. It is proposed that primary deep marine sedimentation processes may have contributed to that initial enrichment. Reluctance to accept that turbidites and intervening pyritic sediments <u>were</u> significantly locally enriched may be attributed to the strict association of gold in vein quartz and present lack of substantial auriferous, pyritic sediments without quartz in the sediment pile. However, processes of lithification, deformation and metamorphism may significantly alter the geochemistry of the original turbidite sediment, a fact frequently overlooked when deducing palaeoenvironmental conditions. Secondly, modern turbidite environments are relatively inaccessible for study and therefore more difficult to interpret in the geological time record (Eriksson, 1980, 1982).

Central Victoria

The Lachlan Province is one of several fold belts which constitute the Tasman Geosyncline of Eastern Australia. Most of the Palaeozoic geology of Victoria is contained within the Lachlan Province. A series of palaeogeographic reconstructions by Kemizys (1978) Cas et al. (1980) and Powell (1983) show development of a series of sedimentary troughs across Victoria in a marginal sea or back-arc basin developed between a continental mass to the west and a partially submerged island arc to the east (Figures 5.13, 5.14). Cas et al. (1980) compare the Wagga marginal sea environment of Cambrian to Silurian age and inclusive of a number of sedimentary troughs, with the present Andaman-Nicobar system. Evolution of the Lachlan Geosyncline occurred over four main depositional stages which culminated in local orogenies and generally caused an eastward shift in sedimentation. Vandenberg (1978) summarized the stratigraphy for each trough across Victoria in relation to these four orogenics episodes which include the Delamerian, Benambran, Bowning and Tabberabberan (Figs. 5.15, 5.16). Comparison with Archaean greenstone belt evolution is worth noting. Early mafic and ultramafic igneous activity of the Cambrian is confined to three narrow N to NW trending belts, which from west to east are known as the Stavely, Heathcote and Mt. Wellington axes. A boninite-low-Ti lavas- MORB (mid-ocean ridge basalt) association suggests that the greenstones represent oceanic crust in a marginal sea environment (Crawford and Keays, 1978) although Crawford et al. (1984) since proposed a complex series of events in an island arc-back arc basin setting. Dark pyritic shales, cherts and tuffaceous rocks separate the greenstones from Ordovician sediments. A flood of continentally derived quartzose detritus followed in the Lower Ordovician building up a very thick, monotonous alternation of low-rank greywackes, shales and slates under anaerobic, bathyl conditions. Greywackes were shown to be turbidity current deposits with dark shales, frequently containing sedimentary pyrite having accumulated during intervening quiescent periods (Singleton, 1965).

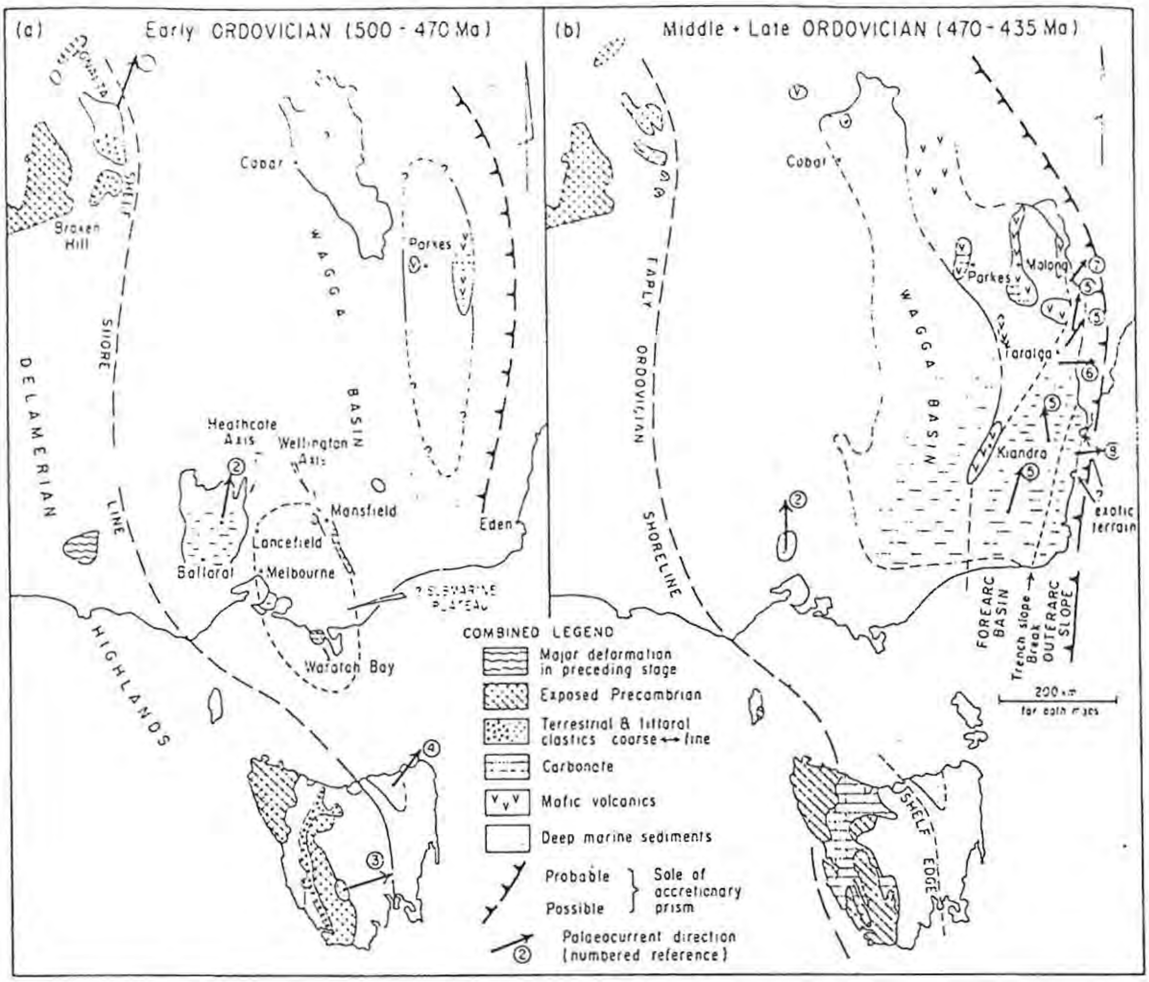


Figure 5.13 Distribution of Ordovician rocks in southeastern Australia. (a) Early Ordovician, (b) Middle and Late Ordovician. Based on Cas (1983, Figs. 7, 8, 9) and Powell (1983a). Numbered palaeocurrent sources: 1, Webby (1976, 1978); 2, Schleiger (1968, 1969, 1974); 3, Corbett & Banks (1973); 4, Powell (unpubl. data); 5, Cas et al. (1980, appendix 1); 6, Powell and Conaghan (unpubl. data); 7, Fergusson (1979); 8, Powell (1983a); (Powell, 1983)

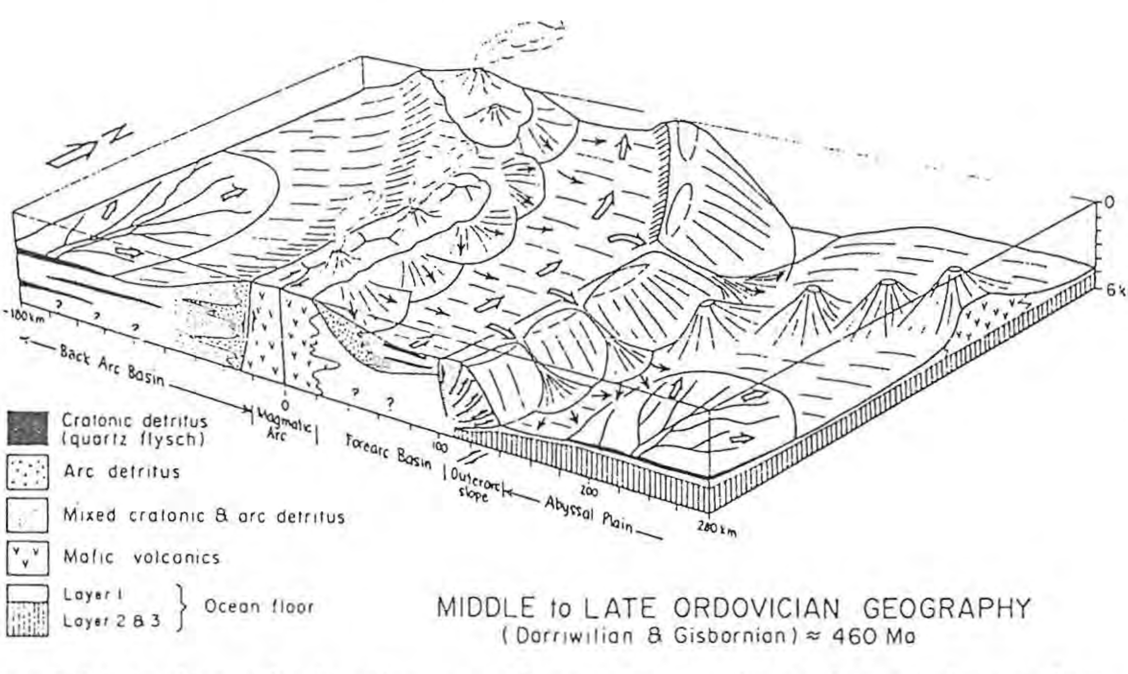


Figure 5.14 Scaled block diagram of Middle to Late Ordovician palaeogeography. Arrows indicate palaeoflow direction (Powell, 1983)

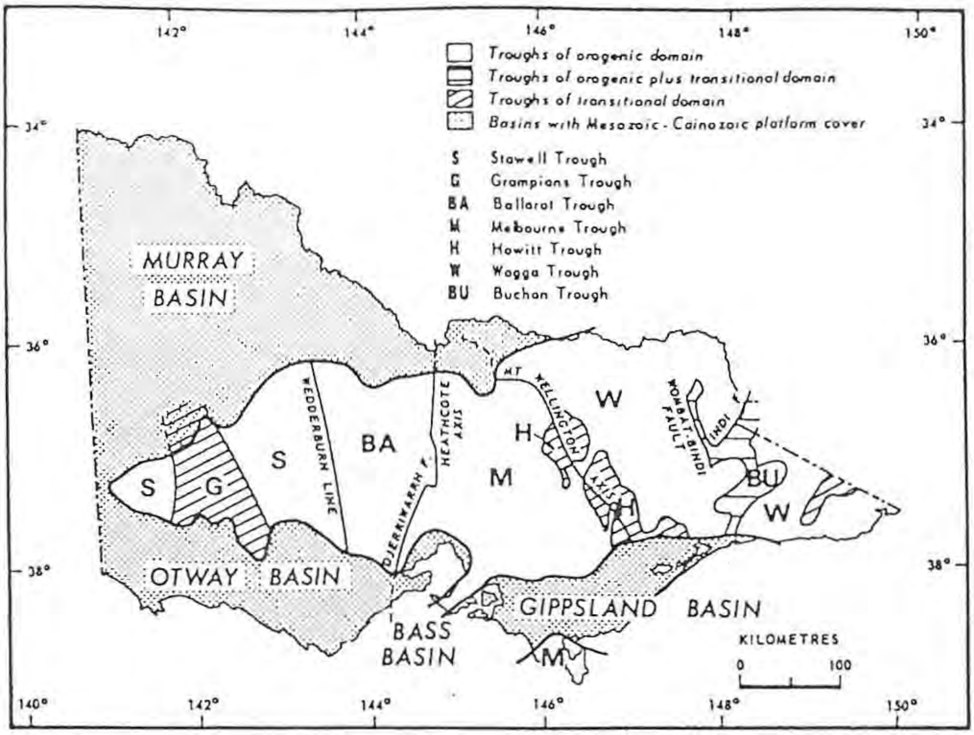


Figure 5.15 Distribution of the main sedimentary basins of the Lachlan Fold Belt in Victoria (Vandenberg, 1978)

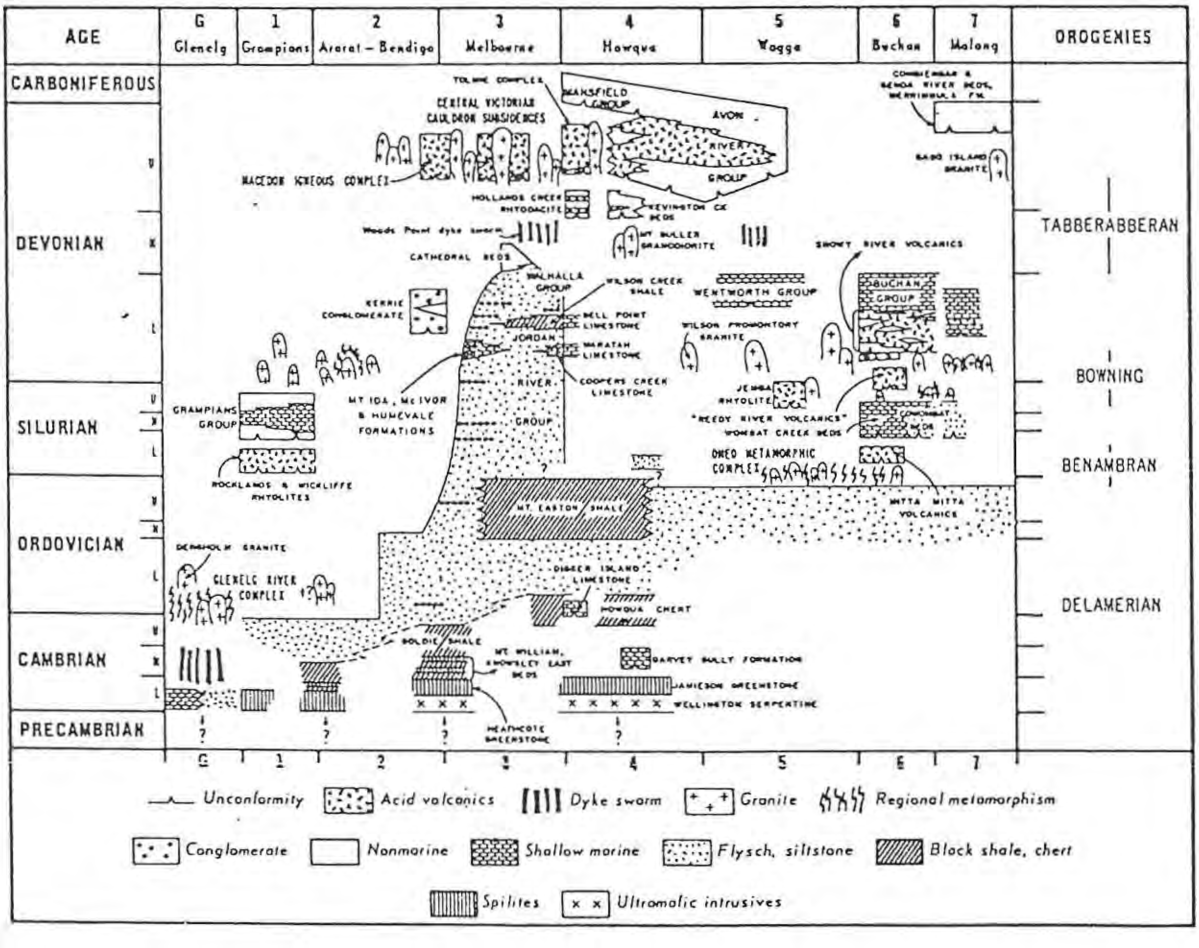


Figure 5.16 Lithofacies correlation chart across the various structural zones (Vandenberg, 1978)

Major goldfields of Victoria are situated west to north-west of Melbourne in a series of N-S trending belts of deformed Cambrian to Lower Ordovician sediments (Fig. 5.17). The Central Victorian region contains a very rich, almost complete sequence of graptolitic faunas making possible a very detailed subdivision of the Ordovician (Powell, 1983) (Fig. 5.18). Although the Ordovician sequence is extremely uniform and monotonous, variations in both thickness and lithologies are evident.

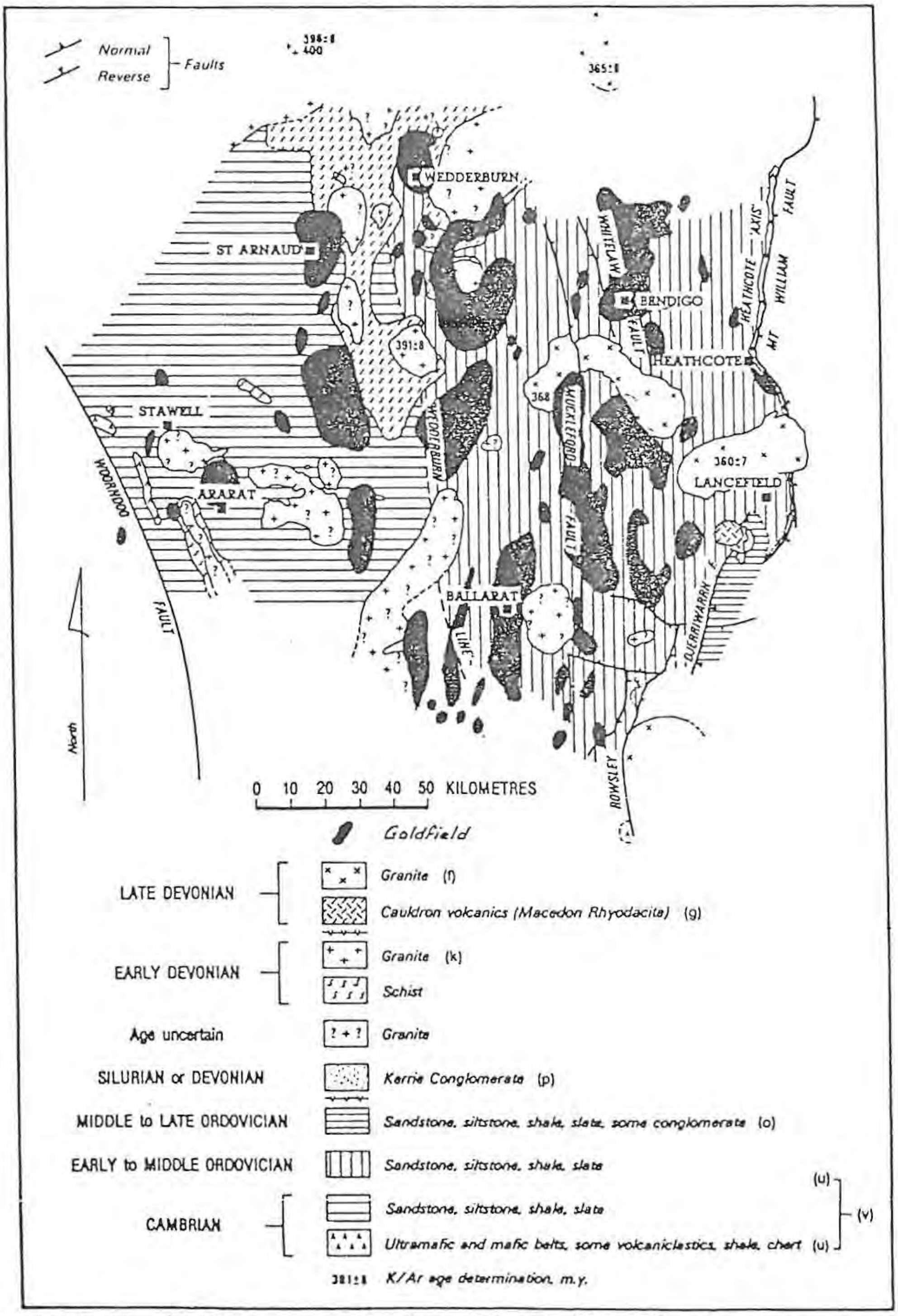


Figure 5.17 Simplified map showing goldfields of the Ararat - Bendigo Zone, with Permian and younger elements deleted (Vandenberg, 1978)

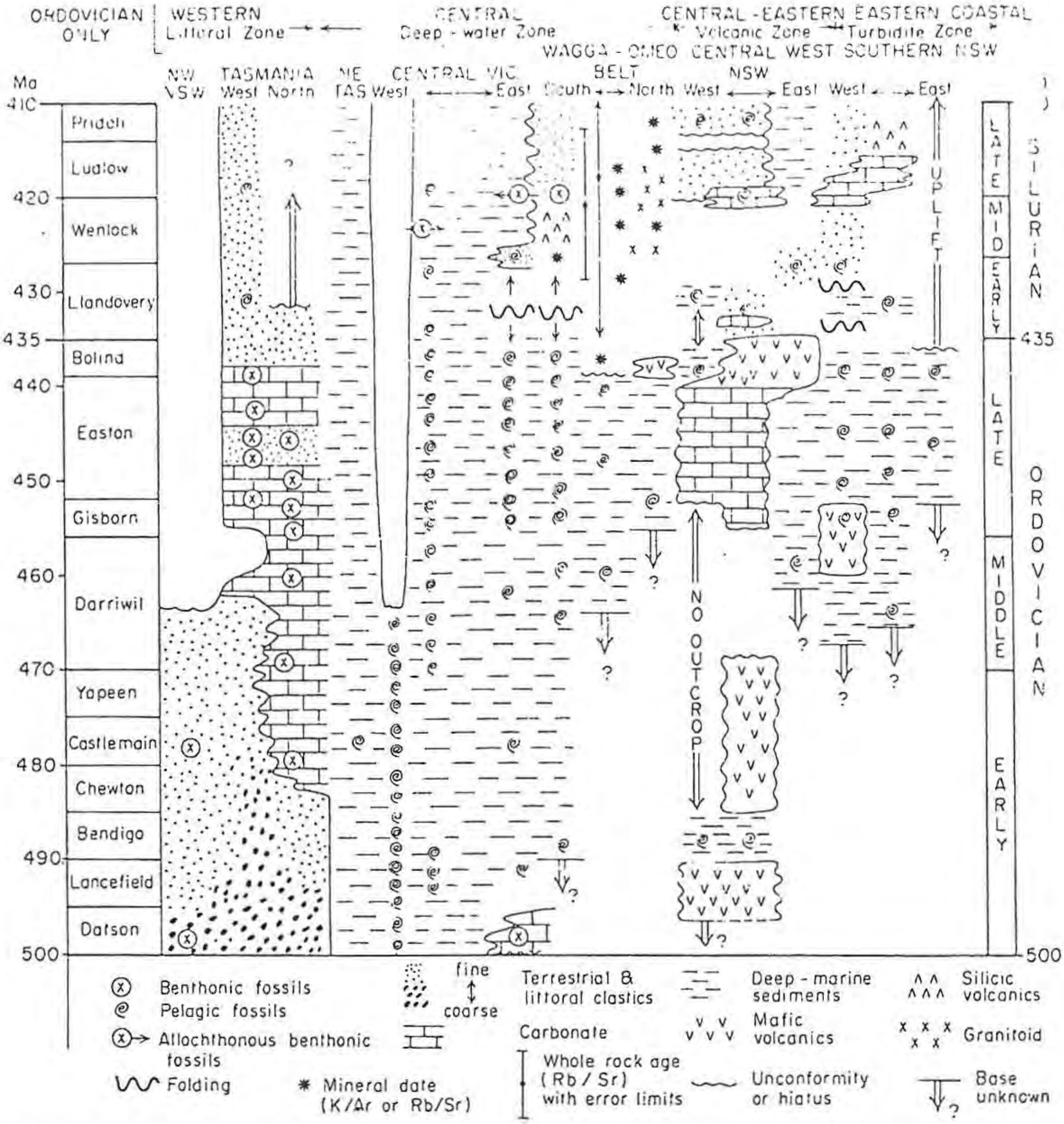


Figure 5.18 Ordovician and Silurian time-space chart west to east across southeastern Australia (Powell, 1983)

Chert bands become conspicuous in sections of slow deposition. Singleton (1965) noted that the Lancefieldian is typically greywacke- dominant with rare shale intercalations compared to the Darriwilian which contains a high proportion of shale. Such variations influenced the behaviour of rocks during formation and had considerable influence on the structural control of quartz reefs and relocalization of gold.

Deformation and metamorphism stabilized part of the westernmost Stawell Trough during the Cambrian-Ordovician Delamerian orogeny but most of Central Victoria stabilized during the Benambran orogeny in the Lower Silurian (Vandenberg, 1978). Granite batholiths intruded the sediments mostly during later orogenic cycles (the Bowning and Tabberabberan) of the Devonian except in the west and far eastern troughs.

The gold deposits formed either during or after deformation of the sediments. Exact age relationships to the granites are uncertain although field evidence suggests they predate intrusion (Glasson and Keays, 1978). The lack of any zonal distribution of goldfields to the granites suggests that a hydrothermal origin from a granite source is unlikely (Bowen and Whiting, 1975).

Five recognized principal gold subprovinces in Victoria include Stawell, Bendigo- Ballarat, Walhalla-Woods' Point, Harrietville and Glen Wills, but by far the most important are those hosted in Lower Ordovician sequences. Goldfields, exceptionally rich in nuggets and characterized by "indicator horizons" were found within the area bounded by Ballarat, Bendigo, Wedderburn and Ararat. Gold production figures from individual mines are detailed by Bowen and Whiting (1975). Substantial quantities of gold were recovered from alluvial and deep lead sources draining the Ordovician terranes but production from lode mines exceeded in importance within 20 years of the initial discovery of gold in 1851.

The majority of lodes consist of gold-quartz veins containing minor sulphides (mainly pyrite and arsenopyrite). Quartz veins occurred as conformable saddle reefs along the crests of anticlines, as laminated reefs along bedding planes, and reefs and spurs along cross faults, irregular fractures and subhorizontal faults. Veins formed variously by replacement of sedimentary horizons, separation of the walls by crystallization pressure of quartz or combinations of these processes, (Stillwell, 1950). Development of auriferous shoots was thought to be dependent on local conditions. Pre-vein open spaces thus appeared unnecessary although Chase (1949) favoured reef formation by fissure filling or fissure filling combined with replacement.

A number of observations by McAndrew (1965) need to be emphasized:-

1) Auriferous reefs formed <u>only</u> along faults with minor displacement and of limited extent. More extensive, commonly brecciated reefs prominent in the broader structural pattern of the lower Ordovician may contain considerable quartz but despite the same age as the auriferous reefs, are barren.

2) Saddle reefs occupied the crests of anticlinal folds, and legs commonly graded down the bedding to conformable laminated reefs. Inverted saddles in synclinal positions were less common (Figs. 5.19, 5.20).

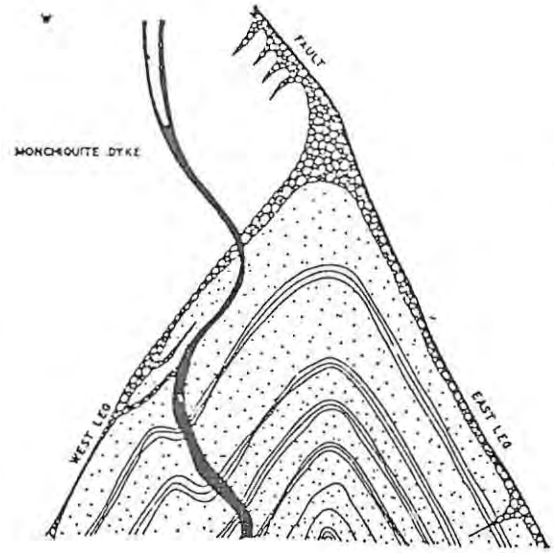


Figure 5.19 Cross section, looking north, of saddle reef on Sheepshead anticline, Bendigo (McAndrew, 1965).

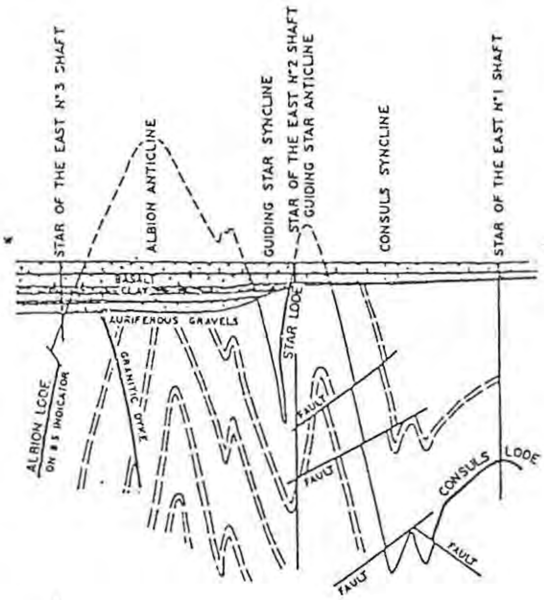


Figure 5.20 Cross section, looking north, through Star of East mine, Ballarat West (McAndrew, 1965)

3) Saddle reefs, at Bendigo, occurred in thirteen adjacent anticlines, uniformly spaced over an area nearly 4 by 20km^2. Folds were sharp with limbs dipping consistently between 65° and 75°. Up to 24 saddle reefs were intersected in one anticline over a vertical depth of 700m (Fig. 5.21). Gold occurrences were more abundant when the fold pitch had a broad domal profile. Saddle reefs were rarely perfectly crescent shaped and completely conformable while a cross- cutting reef extended upwards from the top of the saddle where an associated reverse strike-slip fault changed from a bedding plane fault to a cross-cutting fault. Many faults displaced the anticline less than 1m and died out before reaching the adjacent syncline. Fault displacement up to 30m continued across the strata to a syncline and a bedded fault.

4) Economic mineralization occurred in shoots of variable position in the saddle reefs but frequently was richest in the lower central part and below this along one or both legs. Gold shoots were known to extend along anticlinal crests for up to 2km. At Bendigo east legs produced more gold than west legs.

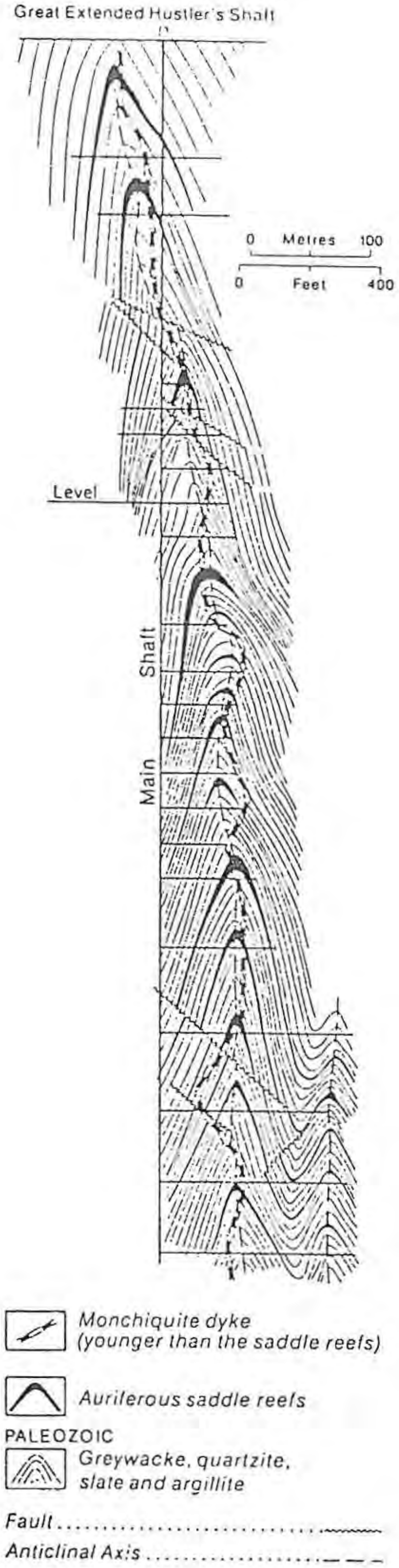


Figure 5.21 Stacked saddle reefs, Bendigo goldfields, Victoria, A(modified from Hermann, 1914) (Boyle, 1979)

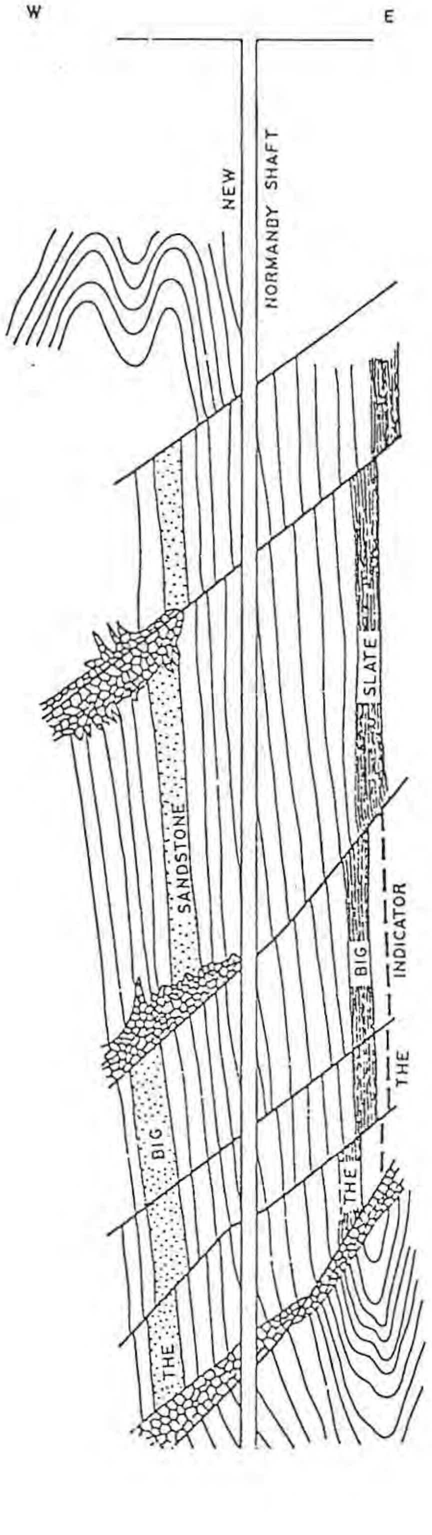


Figure 5.22 Cross-section, looking north, through New Normanby mine, Ballarat East (McAndrew, 1965)

5) The Ballarat West goldfield was notable for conformable lodes which were confined to a 20 to 30m thick horizon containing several carbonaceous, black slate beds. Concordant horizons of laminated quartz with graphitic inclusions and black partings were remarkably continuous along all fold limbs. However, auriferous shoots were confined to fold axes and along west dipping limbs.

6) "Indicator horizons" are narrow seams sometimes only 1cm wide, and vary from carbonaceous slate, to pyritic slate or bedded pyrite seams. Such an "indicator horizon" free from quartz and any evidence of introduced mineralization at Wedderburn varied in gold content from trace amounts to over 1oz/tonne. Glasson and Keays (1978) rejected the possibility that black pyritic slates, ("auriferous slates") may contain high gold by relating gold content directly to pyrite contents, and suggesting that supergene enrichment was responsible for the high assays.

7) Reefs along strike faults and associated spurs were also a major source of gold production from lode quartz. Reefs along cross faults were of only minor importance.

All reefs showed enrichment where they intersected thin favourable "indicator horizons" and a number of these generally black carbonaceous slate bands were traced over considerable distances (Fig. 5.22). Spectacular enrichments frequently were restricted to within 0,5m on either side of the bed. Some sandstone beds were also favourable for enrichment.

Singleton (1965) noted that the "indicator belt" was developed in beds of Lancefieldian or older age in which greywackes predominate over shales. Wherever Lancefieldian beds outcrop on anticlinoria nugget gold became conspicuous and "indicators" important. Payable reefs were apparently absent as high up as the Darriwilian (Refer previous Fig. 5.19).

Reefton Field, Western Sedimentary Belt - New Zealand

Reefton is the most important of several goldfields found in low grade metamorphosed sequences in the Western Sedimentary Belt of the South Island, New Zealand. Over 62 tonnes of gold were produced from epigenetic gold-quartz lodes hosted in Cambrian to Ordovician age greywacke-argillite assemblages of the Greenland Group within a NNE trending belt extending over 34km long and 10km wide (Williams, 1974; Braithwaite and Pirajno, in press). Interpreted as deep water turbidites the quartz-rich greywackes accumulated in a post-arc deep water submarine fan environment (Crook, 1980). The Western Sedimentary Belt represents the most western portion of Tuhua Terrane, a microplate or ensialic segment which rifted from Gondwana in the Middle Cretaceous. Prior to rifting, accretionary processes occurred along a continental plate margin in much the same way as those along the east coast of Australia (Howell, 1980). The age, and environment of deposition of host rocks to the Reefton goldfield are similar to the Central Victorian goldfields and there is no need for furthern description here (Williams, 1974; Braithwaite and Pirajno, in press).

Braithwaite and Pirajno (in press) noted the lack of any clear spatial association between the auriferous veins and granitoid intrusives and considered auriferous lode formation as intrinsic to deformation and metamorphism related to the Greenland event at 395-400Ma. Auriferous lodes of Reefton, unlike those of Ballarat-Bendigo, preferentially followed axial planes of folds on or near synclinal axes, apart from the Blackwater mine and less important producers which followed anticlinal axes. Ore shoots were typically sporadic replacement bodies of quartz, mullock and pug along narrow shears of between 0,6 and 3,2m (Williams, 1974). Gold occurred as free grains and in association with minor pyrite and arsenopyrite. The majority of Reefton lodes were confined to a zone showing the most intense folding and shearing.

In summary, the Reefton goldfield differs from Ballarat-Bendigo fields in:-

1) control of mineralization which is predominantly structural

2) nature of auriferous lodes which are mostly cross-cutting compared to the stratabound tendencies of those in Central Victoria

3) lack of conspicuous influence of host rock lithologies, or the presence of "indicator horizons".

The following chapter will briefly discuss the geochemistry of gold with respect to diagenesis and metamorphism accompanying deformation.

6. DIAGENESIS, DEFORMATION AND METAMORPHISM OF TURBIDITE ENVIRONMENTS

a. Parameters for Consideration

Formation of an ore deposit requires a necessary concentration of metal relative to its average abundance in rocks. Gold in the average crust in the part-per-billion range must be concentrated to the part-per-million level, a considerable enrichment factor. Multi-stage enrichment processes are often invoked to adequately explain sufficient concentration to form an ore deposit (Henley et al., 1976). Ore formation may be considered in terms of source and sink volumes and the coincidence of certain accidents (Fig. 6.1) (Fyfe et al., 1978). Prerequisites for ore formation might include the following:-

1) Source rock present in appropriate volume with an anomalous concentration must increase the odds of ore formation. Keays (1984) recently emphasized the accessibility of gold in a source rock and favoured its association with highly reactive sulphides in mafic and ultramafic magmas.

2) The source rock must have pervasive permeability necessary for efficient leaching or extraction of gold (Henley, 1973a). It follows that cracked source media will be less efficiently leached than porous media (Fig. 6.2).

3) There must be access to an appropriate solvent (normally salty water) in sufficient volumes.

4) A large energy source must be available (thermal or gravitational) to drive the extraction process. For instance, a surficial weathering environment is particularly favourable for ore formation with ultimate energy sources represented by the sun and gravity, and given the permeable nature of surface rocks.

5) Flow velocity and gradients must be appropriate.

6) A focusing mechanism and highly efficient depositional environment.

Fyfe and Kerrich (1984) emphasized the role of fluid interactions (dominantly water) with primary rocks, for processes of gold

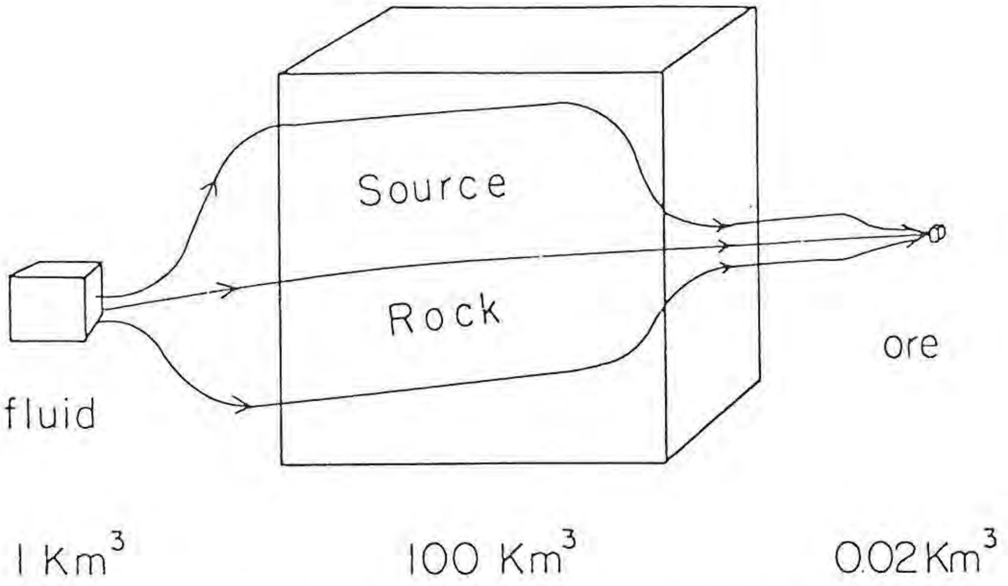


Figure 6.1 The gold extraction problem: a large fluid volume must flow through an even larger rock volume on a microscale and the output for a small volume. In fact, it is better to generate the fluid in situ by metamorphic processes (Fyfe and Kerrich, 1984)

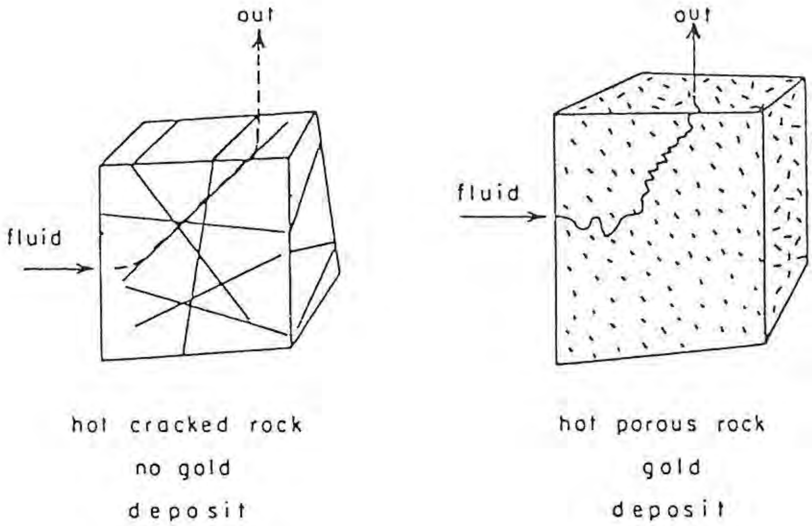


Figure 6.2 Comparison of fluid in a cracked versus a porous (metamorphic) rock. The former may extract an element in the ppm range while the latter is necessary for ppb levels (Fyfe and Kerrich, 1984)

concentration. In the history of turbidite sequences fluid interaction may be considered important in three stages.

1. Primary sedimentation

The very process of turbidite deposition involves grain by grain interaction with fluids. Temperatures are low, waters mostly oxygenated but at the same time thoroughly loaded with particulate matter, dissolved salts and metals derived from erosion and leaching of continental hinterland. Rapid mixing with ocean waters may result in diffuse precipitation over large areas, or given stagnant conditions in bottom deeps localized precipitation may result. The role of oceanic biomass in reactions is grossly underestimated and pelagic sediments underlying and between turbidite layers which are not recycled may represent a significant geochemical sink (Fyfe et al., 1978).

2. Diagenesis

Expulsion of interstitial or connate fluids during deposition may be viewed as a highly efficient interactive process. Dewatering during simple compaction may constitute an ore-forming process particularly with respect to low temperature sulphide ore formation (Hanor, 1979). Diagenetic processes in turbidite sequences may also constitute an enrichment factor in the multi-stage evolution of auriferous veins in turbidites.

3. Metamorphism

Large quantities of fluids are mobilized during prograde metamorphic dewatering and degassing from reactive minerals. Interaction on at least 50% of all mineral grain boundaries of the reactive rock must be expected (Fyfe and Kerrich, 1984). The abundance of epigenetic gold developed in subzones III and IV of greenschist facies rock in New Zealand (Williams, 1965) compared to weaker mineralization in lower textural subzones and rare mineralization in epidote-amphibolite and higher grade metamorphic rocks demonstrates alone the highly efficient extraction of gold under high temperature regimes (Henley et al., 1976).

Study of the geochemical behaviour of gold in each of these environments is receiving increased attention to unravel the extraction-transport-precipitation mechanisms. However, fluids bearing relatively low concentrations of gold may also constitute ore forming solutions provided the appropriate depositional environment is available (Seward, 1984).

In the metamorphic environment mechanisms entail:-

1) primary one-stage hydrothermal extraction in vein conduits mega shears or on the sea floor

2) hydrothermal leaching of materials which have undergone a prior gold enrichment (multi-stage) (Fyfe and Kerrich, 1984).

An equally important consideration during ore formation and multi-stage enrichment are factors of preservation. For example, the state of preservation of a surficial environment which may favour ore formation, is at high risk compared to ore formation in submarine environments.

The geochemical behaviour of gold in a number of environments is well documented including oxidizing near-surface environments, geothermal systems and simulated higher temperature metamorphic regimes (Henley, 1973b; Seward, 1973; Henley et al., 1976; Fyfe et al., 1978; Barnes, 1979; Boyle, 1979; Seward, 1984). Chemical and biochemical reworking during early to late diagenesis and low grade metamorphism in a strongly reducing environment is however less well documented. Such processes are thought to highly modify placer deposits (Boyle, 1984), e.g. the Carbon Leader of the Witwatersrand, and may be significant with respect to gold hosted in deep marine sediments. Seward (1984) further noted the lack of experimental data with respect to the complexing species of gold in very high temperature regimes (viz. 500°C).

By briefly examining the process of diagenesis, structural deformation and metamorphism of gold-hosting turbidites and associated stratigraphy it may be demonstrated that the concentration of gold is subject to a number of constraints. The first and most obvious is the fact that fluids oversaturated with respect to silica and carbonate, and carrying parts per million levels in gold for all intents and purposes were until recently never proven to exist (refer to Boyle, 1979; on the abyssal and magmatic differentiation theory p.391).

However, a deep drilling research well on the Kola Peninsular, U.S.S.R., encountered "copius flows of hot, highly mineralized water" at depths around 4,5km (Kozlovsky, 1984). Levels of concentration in these fluids were not detailed but the discovery of "mineralized" metamorphic dewatering deep in the earth's crust may have far reaching implications with respect to ore formation.

The mineralizing process may be viewed as either continuous or catastrophic. Continuous mineralization requires an efficient focussing mechanism for metallizing solutions, while the depositional environment must remain receptive to promote enrichment from relatively unconcentrated mineralizing fluids.

Alternatively, catastrophic mineralization may represent a "one of" situation if ore-forming fluids derive from deep crustal sources. Water forms the dominant constituent of ore-forming fluids, therefore knowledge of its origin and nature is fundamental to any theory of ore genesis. Study of fluid inclusions provides important evidence with respect to conditions of pressure and temperature, oxygen fugacity, pH and variations in dissolved salts and gases. Roedder (1984) has reviewed the state of the art in fluid inclusion work, including a number of caveats on various gold deposits, and pointed out the value of its application with respect to ore genesis besides its limitations. Fluid inclusion studies may confirm whether or not several mineralizing events were responsible for a single ore deposit.

Isotope studies may decipher the source of water (use of oxygen $^{18}O/^{16}O$ and hydrogen D/H) to determine the origin and history of water in hydrothermal fluids. However, Taylor (1979) emphasized, that any type of ore deposit may conceivably become involved in a later metamorphic episode. Isotopic work according to Boyle (1979) has considerable shortcomings because of isotopic overlap between metamorphic and magmatic fluids. It may be interesting to speculate the consequences of isotopic studies of fluids encountered in the world's deepest well at Kola!

Selected isotopic studies have demonstrated that metamorphic fluids may be introduced into the stratigraphy from elsewhere and refuted lateral secretion theories which support the derivation of metamorphic fluids from adjacent wall rocks. However, this does not preclude overprinting of a resource already present, particularly when fluid pathways are predetermined by bedding partings and fracture systems, often initiated during basin development and simple compaction.

b. Diagenesis of Turbidites

Turbiditic sandstones and shales, of all sediments undergo extreme chemical and physical changes during and after burial. Thermal limits range from a few degrees below 0°C to between 250-300°C (temperature of deeply buried sediments) which begins to mark the realm of metamorphism and re-equilibrium of argillaceous sediments. Sedimentary basins must be viewed as dynamic open systems where both energy (heat) and material (water and dissolved substances) are exchanged with the external

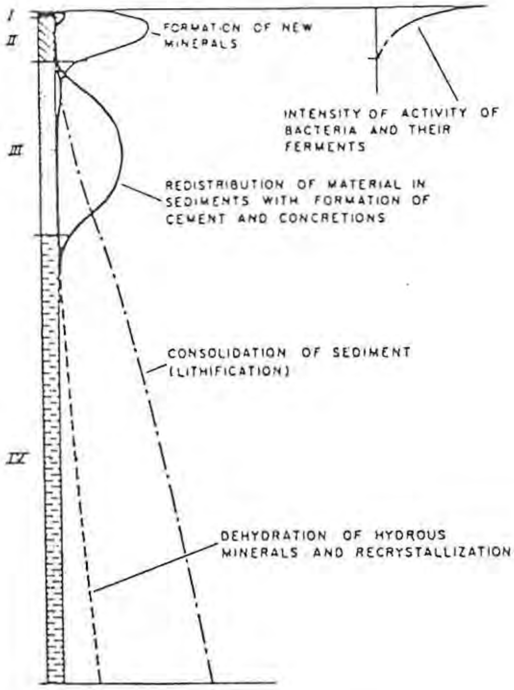


Figure 6.3 Diagenetic stages in sediments (after Strakhov et al., 1954, p.596) (Larson and Chilingar, 1979)

environment. Sediment diagenesis incorporates the migration and chemical evolution of connate fluids which become involved in a complex series of events. Processes are largely non-equilibrium and irreversible (Hanor, 1979).

The principal stages in diagenesis include (Fig. 6.3):-

1) Formation of new minerals
2) Redistribution and recrystallization of substances in sediments.
3) Lithification.
4) Dehydration of hydrous minerals and recrystallization.

Diagenetic minerals formed in the first two stages include Fe^{2+} and Mn^{2+} sulphides, (pyrite and marcasite) and carbonates such as siderite, ankerite, rhodocrosite and oligonite (Larsen and Chilingar, 1979). Turbidites undergo diagenesis in moderately reducing conditions under which gold will form complexes with S_x^{2-} or NH_3 (Barnes, 1979). Seward (1984) favours the transport of gold as thiocomplexes $Au\ (HS)_2$ using a pyrite-pyrrhotite buffer at low temperatures. The presence of organic matter in turbidites may be high. Diagenesis of organics involves a progressive series of decomposition reactions which are mostly irreversible. Low temperature diagenesis involves partly biochemical reactions, incorporating the release of metabolic products to CH_4,

CO_2, H_2S, NH_3, and N_2 (Barnes et al., 1984) which exert a reducing effect on surrounding mineral assemblages (Miyashiro, 1973).

Migration of diagenetic fluids between adjacent layers of sediment will tend to concentrate gold wherever a fluctuation in $f(O_2)$ occurs. That is, gold will tend to concentrate with pyrite and near the influence of decomposing organic matter.

The general process of lithification in turbidites involves

1) cementation by a combination of argillaceous particles and those crystallized from solution;
2) mechanical compaction of sandstone grains with argillaceous binder;
3) a reduction in porosity and permeability by crystallization cements, and
4) final compaction with granular interlock caused by the dissolution of quartz at points of contact (Dapples, 1979a).

The fourth or phyllomorphic stage is characterized by authigenesis of micas and feldspars with development of chlorite and alteration of clays to micas (Dapples, 1979a).

In terms of quantity the redistribution of silica in eugeosynclinal sediments is very high due to the solubility increase of SiO_2 with increasing temperature and a pH values 8.5. Bedded chert capping the e division in Bouma sequences may often result from complex diagenetic replacement of carbonate instead of primary precipitation of either biogenic or inorganic opal. Dapples (1979b) differentiated cherts of bedded marine sediments into those of pelagic and/or diagenetic origin and compared their petrographic characteristics with siliceous shales and porcelanite. Pyritiferous and/or carbonaceous cherts are noted for their gold content and may constitute protore. Natural organic acids may be important for the low energy transport of colloidal gold during early diagenesis (Zumberge et al., 1978). With increasing temperature and depth of burial, dissolution, migration over short or large distances, and recrystallization of chert is to be expected. Diagenesis of turbidites involves either continuous or episodic processes. With increased compaction and a concomitant reduction in porosity and permeability interstitial water and dissolved fluids, would tend to focus between strata than forcibly upwards, and migrate up dip towards the margins of the basin (Hutchison, 1983).

The presence of oraganic matter between Bouma sequences would tend to promote gold enrichment with the continuous passage of even dilute concentrations of gold. Reduced permeability during lithification would focus episodic loss of fluids along planes of weakness initiated by tectonism, and gold would precipitate during migration along temperature-pressure gradients. The morphology and composition of submarine turbidite fans may predetermine a pattern of migration for basinal brines. For instance, fluids may tend to migrate from the deeper, less permeable basin plain shales up dip through buried mid fan channel ways towards faulted scarps at the basin margins where proximal coarser-grained, more permeable strata of the suprafan occur.

Deformation and Metamorphism of Turbidites - a Significant Role in Formation of Epigenetic Gold Deposits

The onset of metamorphism is favoured as the final and most critical mechanism for concentrating gold into structurally controlled vein systems hosted by turbidites. Boyle (1979), one of early exponents of metamorphic secretion, related the origin of many gold deposits to the mobilization and concentration of gold, silver and gangue elements, initially present in the rocks, to available faults, shears, fractures and chemical traps (carbonate rocks). The reader is referred to Boyle (1979) for an exhaustive summary of studies carried out over the past twenty years which have supported the role of metamorphic fluids in the mineralizing process.

Popularity of the metamorphogenic theory is further evidenced by the number of geochemical studies on the complexing behaviour of gold at temperatures up to 500°C (Seward, 1973; Henley, 1973a, b; summary data by Fyfe et al., 1978; Barnes, 1979; Fyfe and Kerrich, 1984; and Roedder, 1984). Quantitative experimental geochemistry is still lacking for the transport and deposition of gold at elevated temperatures approaching processes of granitization (Seward, 1984). However, the efficiency of dehydration reactions in the epidote-amphibolite and amphibolite facies of metamorphism and granites in the mobilization of gold towards middle and lower greenschist facies boundaries (Fig. 6.4) is clearly evidenced by comparing gold contents of sedimentary and igneous rocks in Tables 6.1 and 6.2.

Table 6.1 Gold content of a cubic mile and cubic kilometre of various types of igneous and sedimentary rocks* (Boyle, 1979)

Rock type (Gold content in ppm in brackets)		Gold content/mi^3		Gold content/km^3	
		(g x 10^6)	(oz x 10^6)	(g x 10^6)	(oz x 10^6)
Igneous type rocks					
Ultrabasic	(0.0045)	56.273	1.809	13.500	0.434
Basic	(0.0072)	90.036	2.895	21.600	0.694
Intermediate	(0.0047)	58.774	1.890	14.100	0.453
Acid	(0.0027)	33.764	1.086	8.100	0.260
Sedimentary rocks					
Sandstone, arkose, conglomerate, etc.	(0.0263)	328.882	10.574	78.900	2.537
Shale, mudstone, argillite, etc.	(0.0039)	48.770	1.568	11.700	0.376
Sulphidic schists, pyritic black shale, etc.	(0.0143)	178.822	5.749	42.900	1.379
Tuffs	(0.0023)	28.762	0.925	6.900	0.222
Limestone, dolomite	(0.0034)	42.517	1.367	10.200	0.328
Greywacke and subgreywacke	(0.0076)	95.03	3.055	22.800	0.733

*Data compiled from Tables 13 and 15.

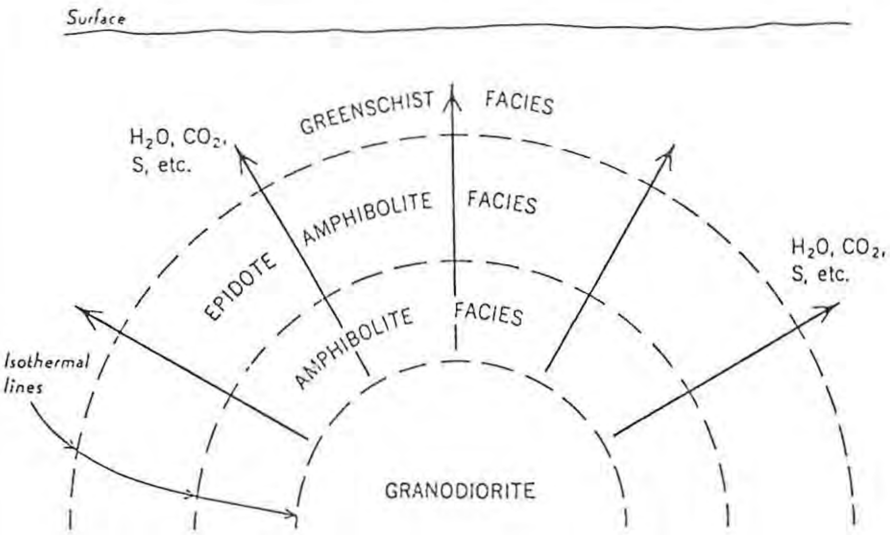
Table 6.2 Gain or loss of volatiles and metals during granitization of a cubic kilometre of greenstone belts, sedimentary belts and ultrabasic rocks (Boyle, 1979)

Constituent	H_2O	CO_2	S	As	Sb	Au	Ag
		(%)					
Content in volcanic (greenstone) belts prior to granitization	1.80	0.262	0.094	7.0	1.0	0.007	0.12
Content in derived granodiorite rocks	0.97	0.084	0.024	2.0	0.2	0.003	0.05
Gain (+) or loss (–) in short tons (or troy ounces) X10^6 during transformation of a cubic mile of greenstone rocks to granodiorite*	–114.4 (–24.9)	–24.5 (–5.34)	–9.65 (–2.1)	–0.069 (–0.015)	–0.011 (–0.0024	–1.608 (oz) (–12.0g)	–28.14 (oz) (–210.g)
Content in pelitic (greywacke and slate) sedimentary belts prior to granitization	3.13	0.30	0.250	20	1.0	0.012	0.20
Content in derived granitic rocks	0.97	0.084	0.024	2.0	0.2	0.003	0.05
Gain (+) or loss(–) in short tons (or troy ounces) X10^6 during transformation of a cubic mile of pelitic rocks to granite†	–297.7 (–64.8)	–29.77 (–6.48)	–31.15 (–6.78)	–0.248 (–0.054)	–0.011 (–0.0024	–3.618 (oz) (–27.0g)	–60.32 (oz) (–450.0g)
Content in ultrabasic rocks prior to granitization	7.80	0.67	0.047	4.0	0.4	0.005	0.08
Content in derived granodiorite rocks	0.97	0.084	0.024	2.0	0.2	0.003	0.05
Gain (+) or loss (–) in short tons (or troy ounces) X10^6 during transformation of a cubic mile of ultrabasic rocks to granodiorite‡	–941.46 (–204.9)	–80.78 (–17.58)	–3.170 (–0.690)	–0.028 (–0.006)	–0.003 (–0.0006)	–0.80 (oz) (–6.0g)	–12.06 (oz) (–90.0g)

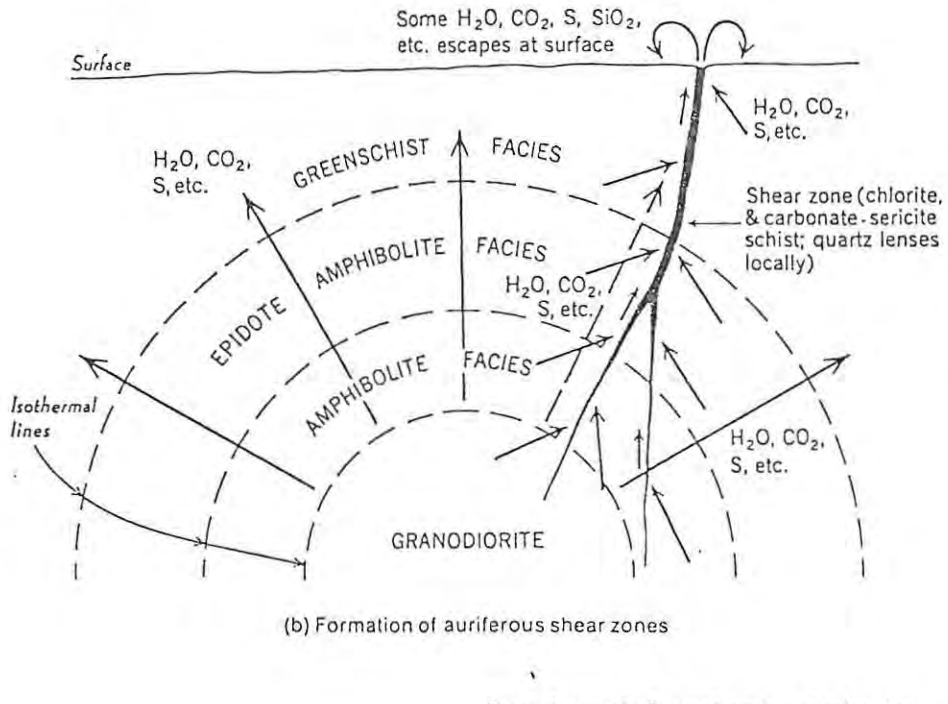
*Numbers in parentheses refer to metric tons or grams X10^6 gained or lost during transformation of a cubic kilometre of greenstone rocks to granodiorite.
†Numbers in parentheses refer to metric tons or grams X10^6 gained or lost during transformation of a cubic kilometre of pelitic rocks to granite.
‡Numbers in parentheses refer to metric tons or grams X10^6 gained or lost during transformation of a cubic kilometre of ultrabasic rocks to granodiorite.

Miyashiro (1973) recognized four main classes of metamorphic reactions:-

1) Solid-solid (no volaties are liberated).
2) Dehydration (water is the dominant fluid component released during metamorphism and volumes increase with rising temperature).
3) Decarbonation (liberation of CO_2 is accompanied by a rise in temperature).
4) Oxidation-reduction.



(a) Formation of metamorphic facies



(b) Formation of auriferous shear zones

Note: Arrows indicate direction of migration of H_2O, CO_2, S, As and other elements

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Figure 6.4 Schematic diagrams illustrating the formation of metamorphic facies and auriferous shear zones (Boyle, 1979)

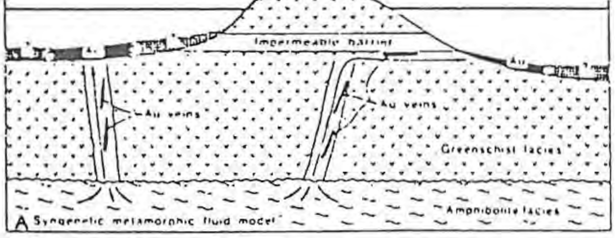

Figure 6.5: Syngenetic metamorphic fluid model adapted from Kerrich and Fryer (1979) (Phillips et. al., 1984)

The latter three reactions are particularly relevant to the leaching, transport and reprecipitation of gold. The effect of increasing metamorphic grade with the burial of Archaean or younger greenstone belt stratigraphy (in the uniformitarian sense) has the effect of driving any gold remaining in the underlying mafic-ultramafic volcanic pile, and protores represented by chemical sediments and auriferous banded iron formation into the overlying turbidite sequences. Concentration of gold into epigenetic vein systems of Archaean greenstone belts is influenced by the metamorphic zonation imposed by rising tonalitic and granodioritic batholiths (Anhaeusser, 1976 and Viljoen, 1984). Kerrich and Fyfe (1981) further suggest that metamorphic-generated fluids may exhale at surface to create a syngenetic deposit (Fig. 6.1). Exhalation of such fluids may be considered partly responsible for the deposition of banded iron formation and cherty metasediments during turbidite deposition. Thick turbidite sequences overlying progressively metamorphosed volcano-sedimentary strata at depth, represent largely impermeable capping strata. Should the turbidite wedge lie beyond the range of influence of prograding high grade metamorphism, a number of features are favourable for the entrapment and concentration of gold:-

1) The reducing nature of the sediments and tendency for organic-rich layers to locally depress oxygen fugacity (fO_2) and hence dramatically decrease the solubility of gold. White et al. (1981) compared the discontinuous change in fO_2 or phase separation of CH_4 and H_2O accompanying the reaction between graphite and hydrothermal solutions as a type of "boiling".

2) Monotonous thicknesses of turbidite sequences are regularly punctuated by organic-rich and fine clay-silt layers at the tops of Bouma cycles (division e). This enhances the probability that gold will be trapped by a series of potentially reactive layers which are otherwise separated by non-reactive layers (Fyfe and Kerrich, 1984).

3) The impermeable nature of the sediments causes localized pressure-temperature increases in dehydration waters which then induce hydraulic fracturing (Fig. 6.6). Different parts of the turbidite sequence may be more amenable to brittle versus ductile failure and influence the passage of solutions. The presence of gold may be therefore broadly related to stratigraphy (Ransom and Hunt, 1981).

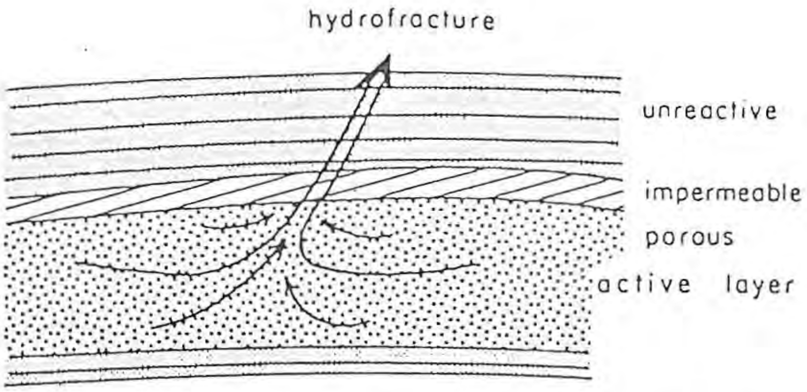

Figure 6.6 Possible flow path of metamorphic fluids from a reaction layer through impermeable convective layers (Fyfe and Kerrich, 1984)

4) Faults and fractures in turbidites represent a focusing mechanism for the passage of large volumes of dehydration products in solution. However, Glasson and Keays (1978) drew attention to the fact that only a small volume of SiO_2 (0,1wt% at the greenschist-zeolite facies transition) released from metasediments during metamorphism is actually deposited with gold while the rest is discharged through the reef system. Fyfe and Kerrich (1983) therefore proposed that gold-bearing veins were precipitated from hydrothermal solutions which outgassed over a narrow, high-temperature interval in a prograde regional metamorphic regime.

5) High geothermal gradients in deeply buried marine sediments will enhance precipitation of gold in response to falling pressure due to O_2 influenced by cooling of the fluids. Wall rock reactions due to the presence of carbonaceous shale or carbonate in the turbidites (lower PCO_2) will also mediate precipitation (Fyfe and Kerrich, 1984).

6) Rather slow or episodic flow rates with no fast venting (streaming velocities) will promote precipitation and would be expected in thick sequences of turbidites. Alternatively, hydrofracturing accompanied by sudden pressure-temperature decrease and boiling of fluids, may have a dumping effect with rapid precipitation of metals from solution.

7) Presence of clays and pug along fault zones and shears will tend to promote adsorption of gold by clay particles.

Fyfe et al. (1978) favour the onset of prograde metamorphism for the triggering of deformation. That is, the generation of fluids at high pressures produced in the earliest dehydration reactions enables the overlying wet sediment pile to be weakened and to react to existing tectonic stresses in the system (Fig. 6.7).

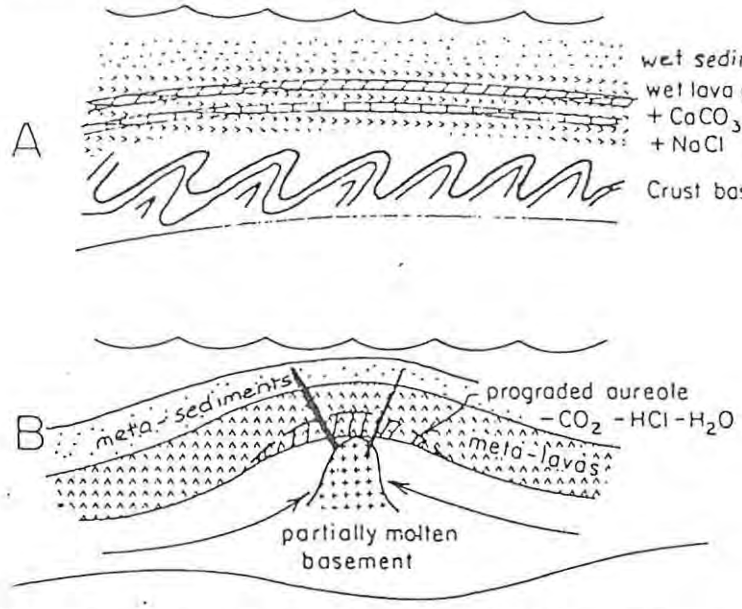

Figure 6.7 A typical Archaean scenario. Complex metamorphic basement is covered with lavas and sediments. A) The loaded, well-depressed basement responds by partial melting of "granitic" doming B) Prograde metamorphism in the aureole of wet volcanics and sediments leads to gold leaching with focussed flows in extensional fractures (adapted from Fyfe and Kerrich, 1984)

As dehydration progrades from depth in a turbidite sedimentary pile so is porosity and permeability reduced at depth. The onset of higher grade metamorphism with temperatures near or above 500°C induces a multitude of micro- and macro-scale hydraulic fractures which permits wholesale leaching of the rock pile. The dramatic change in porosity and permeability results from the breakdown of hydrated minerals in the rock.

The concept of prograded metamorphism (or dehydration) is made complex in the presence of thrusting regimes. Large plate tectonic thrust velocities will prevent thermal equilibrium during thrusting and the final thermal gradients will be nearly as in Figure 6.8. While the lower part of plate A will be retrograded by colder rising fluids, all of plate B will be degassed, and suffer prograde metamorphism. Gold deposition will not occur in the lower part A but would tend to occur in the upper part of plate B to which large volumes of fluids are degassed in the formation of higher grade metamorphic rocks in the lower part of plate B (Fyfe and Kerrich, 1984). This concept, although complex may have interesting implications with respect to accretion tectonics, and even

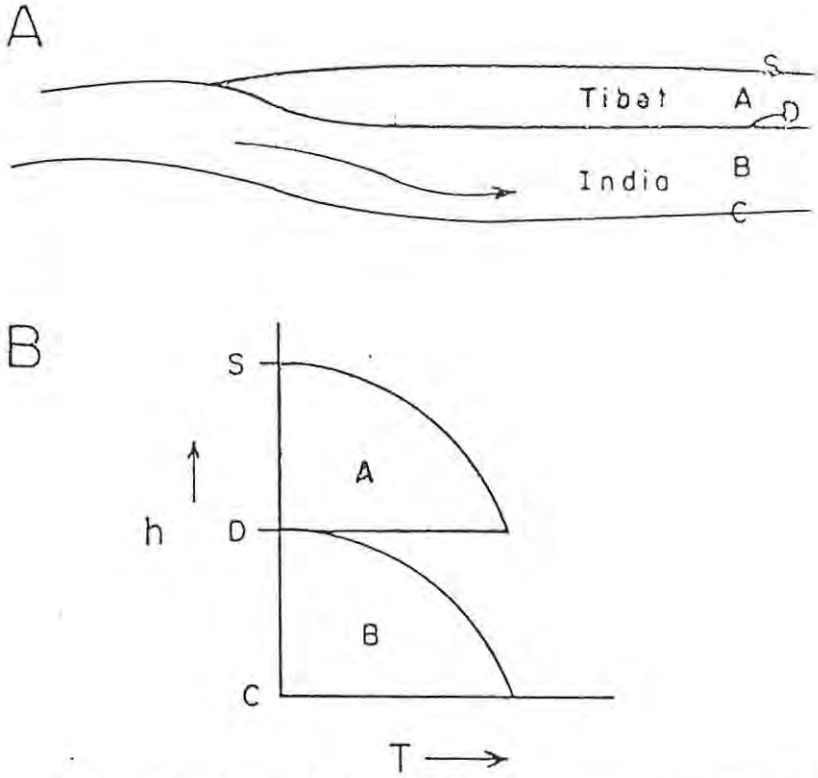

Figure 6.8 A. Crust structure of double thickness formed by thrusting (see Barazangi and Ni, 1982). B. A major prograde metamorphic event occurs in the tip of the underthrust caused by the relaxation of the after-thrust temperature structure (Fyfe and Kerrich, 1984)

begin to take effect during early diagenetic stages. As thrusting progresses dynamic localized dewatering between thrust slices redistributes gold according to local pressure-temperature gradients (refer previous figure). Just as metamorphism and deformation serve to concentrate gold, under certain circumstances these mechanisms may just as easily disperse an original protore concentration.

It might be argued that the richest gold resources require preservation close to their original source e.g. the high silver content of Witwatersrand gold suggests proximity to source terrane (Pretorius, 1984). Just as alluvial and fluvial systems mechanically rework gold in streams and delta fans, much of the eroded gold is eventually lost to the oceans. The same principle may apply to epithermal (Keays, 1984) and metamorphic processes. In this respect patterns of metamorphic and deformation history characteristic of certain plate tectonic settings are important considerations for the early concentration and preservation of gold.

In back-arc regions shortening across the basin and prograded metamorphism from depth in the case of Palaeozoic and Early Proterozoic "greenstone belts" and from the boundaries of Archaean greenstone belts are favourable for localizing rich gold deposits in the *lowermost* sections of turbidite stratigraphy. Accretion tectonics, responsible for the accumulation of considerable thickness of turbidites and their intense deformation during thrusting may have the effect of dispersing gold higher up in structural stratigraphy and further from the original source rocks. That is, assuming the gold is originally of magmatic origin. Although gold is preserved in the rock pile, albeit concentration within structural traps *predictability* of the whereabouts of gold becomes less and less certain.

7.0 A PROPOSED MODEL OF ORE GENESIS IN THE TURBIDITE ENVIRONMENT

Stages in the process of ore formation deal with source and sink terranes and a mechanism of transport. Auriferous veins hosted in turbidites may derive their gold from the turbidites themselves or from underlying lithologies during metamorphism. If the turbidites do represent a source terrane on a protore basis, then both the sediment and gold are derived from yet another source. The cycle begins to emerge. Features of the proposed model are tentative at best.

Despite the emphasis of this model on major (world class) goldfields, including turbidite-hosted gold deposits of the Barberton Mountain Land, the Ashanti goldfield and Central Victorian goldfields, a number of characteristics will apply equally to smaller producers. The model is intended to cater for regional geological exploration purposes, rather than detailed exploration on a vein by vein basis.

1. Geotectonic setting and age

Back-arc bordering on magmatic arc of Archaean and Early Proterozoic greenstone belts and Palaeozoic geosynclines host major goldfields. Lesser gold deposits occur on Middle to Late Proterozoic passive continental margins which border Archaean cratons.

2. Primary Depositional Enviornment

Gold-hosting turbidites form in steep troughs adjacent to a volcanic arc within a marginal sea or narrow oceanic environment, protected from open ocean current circulation. Palaeozoic turbidites are dominated by major influxes of mature terrigenous material from continental hinterlands (Central Victoria; Reefton, New Zealand). Volcanic detritus is more common in turbidites of Archaean greenstone belts (Barberton Mountain Land) and adjacent to volcanic centres of the Proterozoic (Ashanti, Ghana) and Palaeozoic. Thick turbidite sequences stratigraphically overlie or undergo facies change to a large proportion of organic, pelagic and chemical sediment, particularly in the lowermost sections of the stratigraphy (basin plain facies). Turbidites prograde across a predominantly chemical facies which mark the close of an earlier volcanic cycle (e.g. Goldie Shales of Central Victoria; Lower to Upper Birimian Contact, Ghana; Zwartkoppie iron formation, Barberton).

Such facies may be regarded as a geochemical sink. Waning volcanism accompanied by reduced heat flow causes rapid trough-like subsidence. Turbidity current deposition by nature is punctuated by a series of diastems which also mark the accumulation of fine-grained bio- or chemogenic sediment. The proportion of such sediment is often small (e.g. 1% in Central Victoria), (Glasson and Keays, 1978). Sediments and associated turbidites facies of Mid-Proterozoic basins or passive continental margins rest on older cratonic terranes (Yeneena Group sediments overlie the older Paterson Orogen, Western Australia; Transvaal Supergroup rests on Archaean gneissic basement).

Protores of primary sedimentary origin may constitute a significant stage in the formation of an economic gold deposit. Gold may be introduced into the primary depositional environment via:-

1) Deep-seated megashears. Rift-related faults, which control basin subsidence may tap hot metal-laden solutions derived from high grade metamorphism in the lower crust (e.g. Paterson-Musgrave Trend, Western Australia).

2) Discharge of epithermal solutions. Late-stage metasomatic fluids leach the volcanic pile of gold and sulphides and drain into adjoining troughs. Otherwise, metals are leached by seawater reacting with lava flows on eruption. The gold initially is introduced by high temperature, sulphur-undersaturated (that is precious metal-enriched), mafic and ultramafic magmas. (Onverwacht Group, Barberton; Upper Birimian volcanics, Ghana; Cambrian greenstones, Central Victoria).

3) Discharge into the wet sediments pile by diagenetic waters removed from compacted sediments deeper in the basin.

4) Discharge by major rivers. Erosion of continental hinterlands and reworking by alluvial and fluvial processes in rivers and off-shore braid plains may concentrate gold mechanically. Very fine "flour" gold will discharge with fine silts, clays and organic detritus. Coarse gold may be flushed into a trough during erosion of continental-slope environments with increasing subsidence.

Streaming associated with discharge of hot thermal solutions either of deep-seated metamorphic or shallow convecting epithermal origin will carry gold to points of exhalation on the sea floor. Precipitation will proceed due to mixing with lower temperature seawater and gold will be preferentially scavenged by ferruginous sulphides, carbonates and organic-rich silceous gels in bottom reducing conditions. Reworking in bottom deeps is minimal in partially closed, marginal seas while terrigenous influx with turbidity currents will ensure preservation of the introduced gold (Fig. 7.1).

Apart from alluvial and organic concentrations prior to turbidite deposition, low temperature fluid interactions associated with major draining systems and their subsequent discharge into submarine turbidity fans are not expected to concentrate gold significantly during primary sedimentation. Redistribution of gold, metals and organics in the poorly sorted turbidite environments may take place once diagenesis begins.

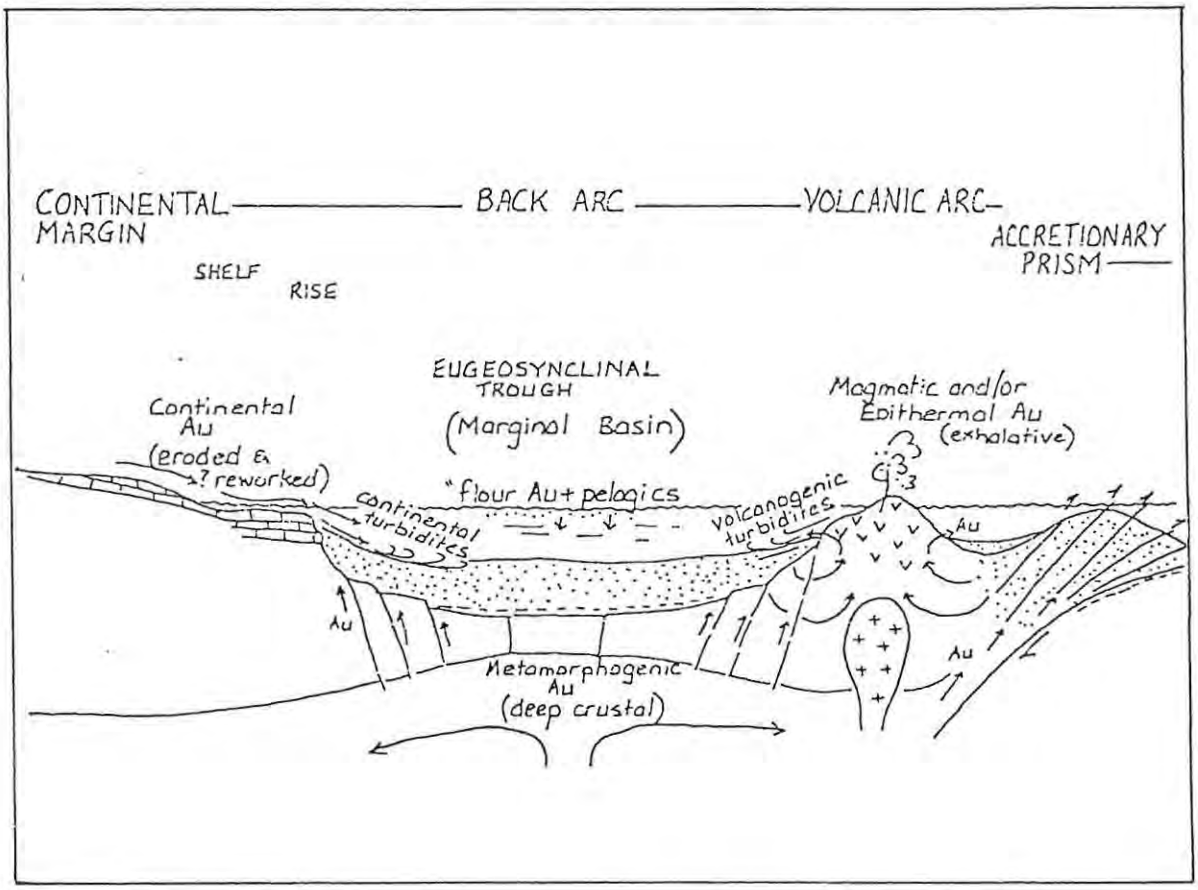

Figure 7.1 Model showing postulated sources and concentration of gold in the primary depositional environment of turbidites

3. Diagenetic Processes

Low temperature, dewatering accompanies burial of turbidite sequences during progradation of a submarine fan and continued subsidence. Redistribution of dissolved particulate matter and metal accompanies migrating basinal (connate) waters which focus updip towards lower pressure regimes and according to permeability factors, (along bedding partings, through coarser grained beds).

As turbidites proceed to lithification, porosity and permeability is reduced, thereby causing partial entrapment and heating of pore waters, which respond by becoming heated and more effective solvents. Gold already present in the sediment pile may be redistributed during migration of low temperature brines accompanying decarbonation of organics, and desilication processes. Gold may be also introduced from the discharge of epithermal or higher temperature metamorphogenic solutions which ascend from deeper levels into the dewatering "wet" sediment pile and mix with lower temperature basinal brines. Precipitation of gold will favour localized more reducing conditions particularly in association with diagenetic sulphides (e.g. pyrite), silica and carbonaceous shale and may accompany partial replacement. (e.g. MVR shale of Telfer, carbonaceous shales of the Black Reef-Malmani transition, "auriferous slates" of Ballarat-Bendigo and Stawell). Ore-bearing shales and protores will assume sedimentary features but may be better described as syn-diagenetic (Fig. 7.2).

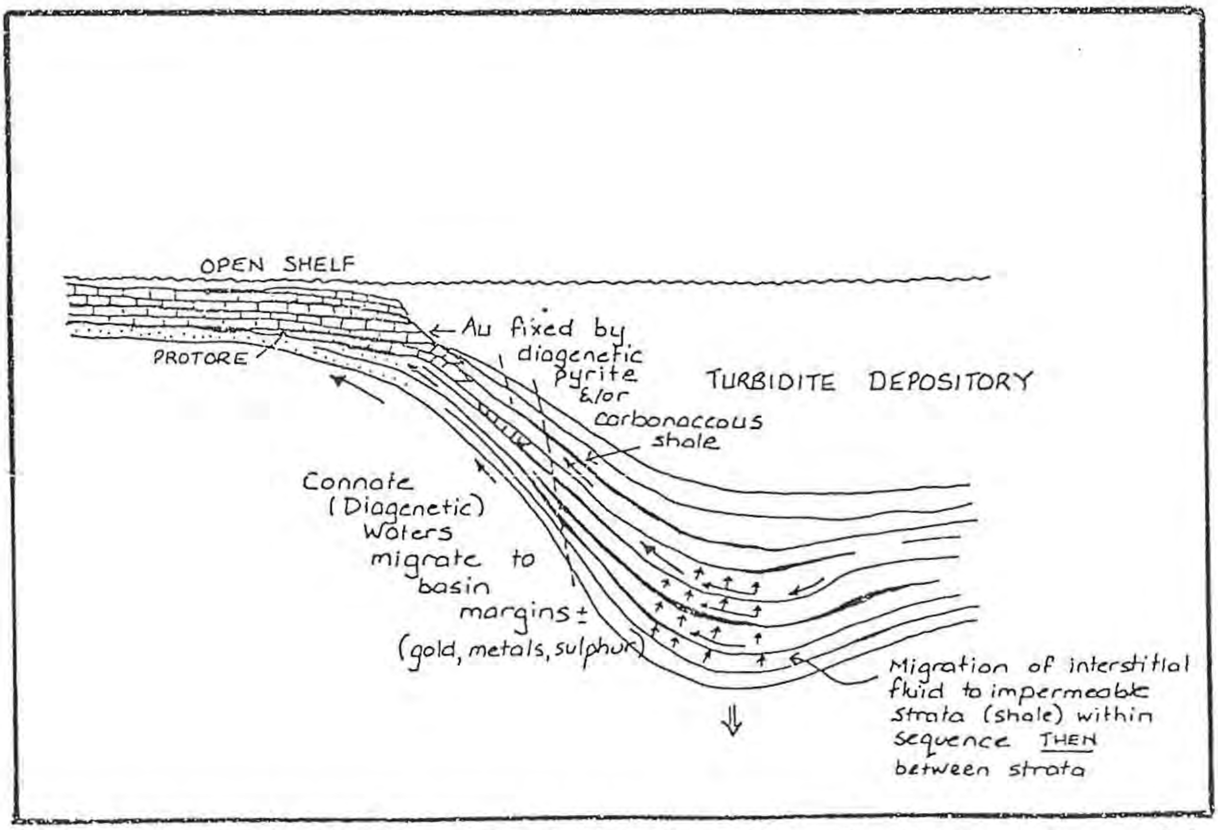

Figure 7.2 Model showing the up-dip migration of connate brines with diagenesis, and possible introduction of epithermal and/or metamorphogenic fluids into the wet sediment pile.

In a marginal back-arc basin or passive continental environment basinal dewatering will focus towards the basin margins and continental slope areas. Faulting along the trough margins may divert migrating fluids upwards. Turbidite fan morphology may also influence the pattern of migration. Accretion tectonics in the forearc region with thrusting of turbiditic "packets" during subduction will complicate the patterns of migrating connate waters.

Metamorphic Processes

Prograding metamorphism from depth during basin infill in a back-arc environment will focus dehydration waters upwards. Highly efficient solvency accompanies higher temperature regimes which induce micro- and macro-fracturing through the rock pile. Metal-enriched solutions migrate within the high temperature zone with ease due to increased porosity and permeability. The upward transition from ductile to brittle (high temperature to low temperature) regimes accompanies a sudden drop in permeability. Faulting and hydrofracturing release pressure-temperature increases accompanying dehydration reactions and metamorphogenic waters are channelled into structural features, which either terminate to become traps or pass through the turbidite pile. Gold is either mobilized from protore enrichments developed in a primary, diagenetic or previous metamorphic environment in the rock pile and/or introduced from deeper crustal levels. Concentrations of gold derive either from the continuous passage of hot metamorphogenic solutions through reactive wall rocks, or by a reduction in pressure/temperature during catastrophic dewatering (Fig. 7.3). At temperatures T 400°C gold is probably transported by simple chloro- and hydroxychloro-complexes (Seward, 1984).

The most spectacular enrichments of vein-hosted gold in turbidites exhibit strong combined structural and lithological control (e.g. nugget effect found near "indicator" horizons, Ballarat), and occur in the lowermost sections of a thick turbidite pile. Mineralization largely depends on focusing mechanisms from dewatering at depth and the grade of metamorphism. Gold may be enriched in a multi-stage prograded metamorphic environment but as it is displaced higher up in the turbidite sequence and shows predominantly structural control the predictability of its whereabouts becomes less and less certain.

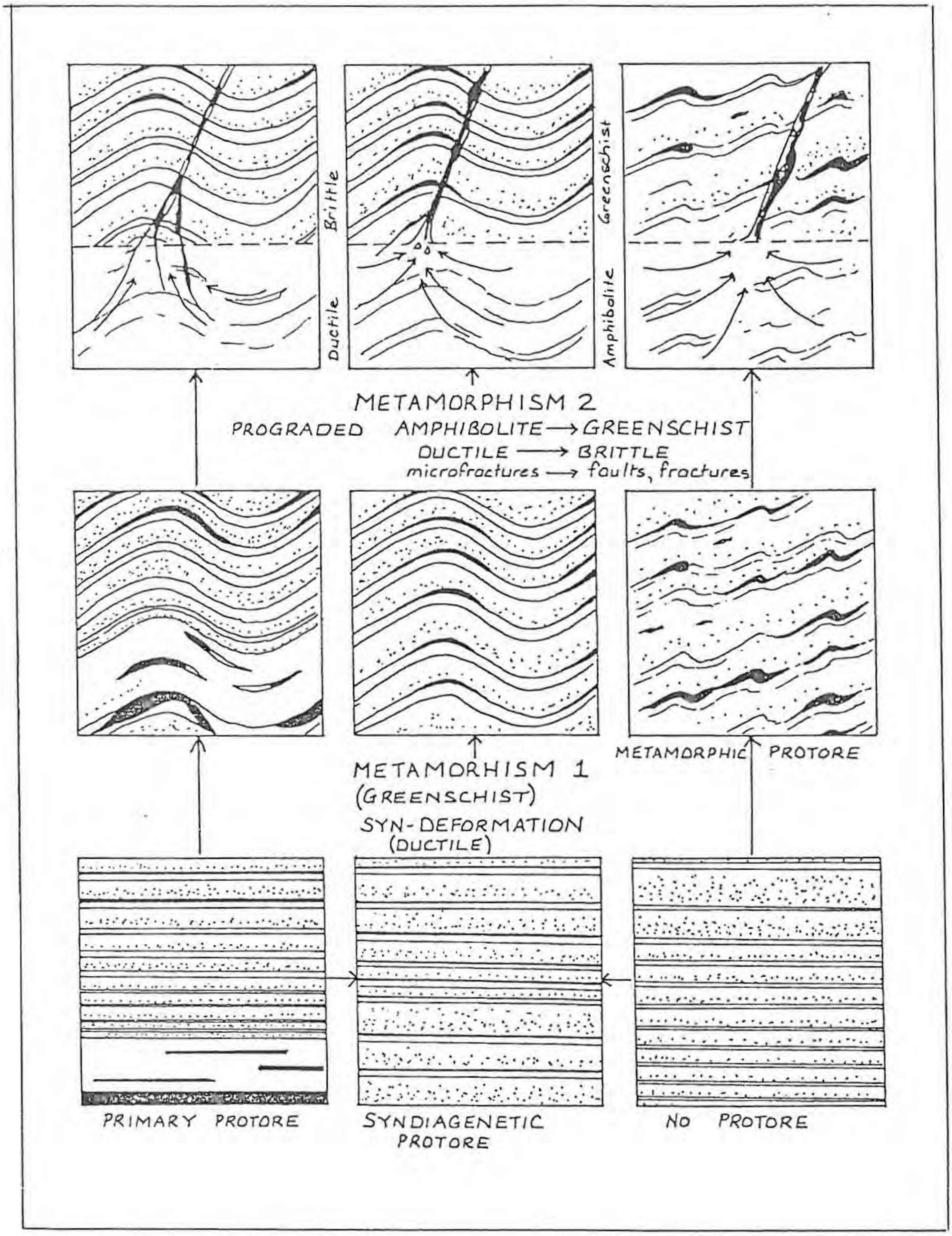

Figure 7.3 Multi-stage metamorphogenic model showing the concentration of gold either from protore enrichments of sedimentary and/or diagenetic origin or previous metamorphic episodes.

8. CONCLUDING REMARKS

A better working model for the exploration of gold should encompass all processes and observed geological features within a host-rock environment which contribute to the metallogenesis of gold.

1. Back-arc basins developed behind magmatic arcs and bordering on passive continental margins represent the most favourable geotectonic setting for the introduction, accumulation and preservation of gold in turbidites.
2. Archaean and Proterozoic greenstone belts display gross simularities to the evolution of selected Palaeozoic geosynclines (in back-arc settings) and together may constitute important gold provenances on a global scale.
3. Palaegeographic reconstruction on a regional and local scale within thick turbidite accumulations in relation to gold mineralization may differentiate parts of the submarine fan which are more amenable for gold concentration whether in a primary, diagnetic or metamorphic environment. Spatial association of gold mineralization to protore enrichments in both a structural and stratigraphic sense may be demonstrated.
4. Patterns of migration during dewatering accompanying diagenesis and metamorphism, may be predetermined by the morphology and development of the original turbidite basin. Metamorphic facies and the style of deformation superimposed on the turbidite pile will strongly influence the process of dewatering, relative solubility of gold and passage of metal-enriched fluids.
5. Non-reactivity of alumino-silicate greywacke-shales and substantial thicknesses of eugeosynclinal successions will tend to promote circulation of high-grade metamorphic metal-enriched fluids in deeper crustal levels prior to hydrofracturing and focused emplacement. The presence of thin seams of reactive, reducing carbonaceous strata dispersed throughout the rock pile will influence the localized precipitation of gold, as the bulk of the solutions discharge.

Multi-disciplinary research incorporating sedimentology, structural analysis and metamorphic petrology of goldfields hosted in turbidites will no doubt elucidate aspects of ore genesis beyond the scope of this dissertation. Isotopic, fluid inclusion and whole rock geochemical studies would also contribute valuable information to the multi-faceted genetic model.

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