GEODYNAMICS, RIFTING, STRATIFORM AND STRATABOUND MINERAL DEPOSITS

D.R.W. DINGEMANS

This dissertation is submitted
as an integral part of the
Mineral Exploration course for
the degree of Master of Science
at Rhodes University

January 1981

This dissertation was prepared
in accordance with specifications
laid down by the University and
was completed within a period of
ten weeks full-time study

ABSTRACT

Stratiform and stratabound ore deposits commonly show a direct relationship with rifts. This association is studied by developing a geodynamic model of mantle processes and crustal responses. The geodynamics of the earth can be modelled by the process of mantle advection, which involves the episodic generation and segregation of low density mantle diapirs and their rise and subsequent interaction with the crust. The theory of mantle advection explains the genetic association between rifting, magmatism, basin development and subsequent orogeny and metamorphism. Global evolution has passed through a number of major stages of non-uniformitarian development in which each cycle was characterized by fairly uniform behaviour terminated by intense geodynamic upheaval. The relationship between geological evolution and mantle advection is examined by reviewing the major characteristics of each of the cycles, which correspond to the Archean, Early Proterozoic, Mid Proterozoic, Late Proterozoic-Palaeozoic, and Mesozoic - Cainozoic eras. Although mantle advection has controlled crustal processes throughout time, the decrease in the thermal energy of the earth has caused the major evolutionary changes in response to thickening and a greater rigidity of the sialic crust.

Rifts are penetrative taphrogenic faults in the earths crust which act as major conduits for the transfer of magmas, from the mantle and lower crustal levels, to the upper crust and the surface. Rifts are also permeable zones for the migration of metalliferous brines, generated by magmatic differentiation. These metalliferous brines would either be exhaled at surface to form stratiform volcanogenic and volcanosedimentary ore deposits, or would interact with preferential host horizons to form stratabound ore deposits. The association between rifting and stratiform and stratabound ore deposits is illustrated by examining the tectonic setting, and stratigraphic relationships of typical ore deposit types.

GEODYNAMICS, RIFTING, STRATIFORM AND STRATABOUND MINERALIZATION

A GEODYNAMIC MODEL 1

MANTLE ADVECTION: A MODEL OF MANTLE PROCESSES 1

CRUSTAL RESPONSES TO MANTLE ADVECTION 11

MAGMATIC ACTIVITY: A RESPONSE TO MANTLE ADVECTION 16

THE GEOLOGICAL EVOLUTION OF THE EARTH 24

THE ARCHEAN 24

THE EARLY PROTEROZOIC 28

THE MID PROTEROZOIC 38

THE LATE PROTEROZOIC AND PALAEOZOIC 44

THE MESOZOIC AND CAINOZOIC 56

- The East African Rift-Red Sea System 58
- The Basin and Range Province and the Rio Grande Rift 67
- Sea-Floor Spreading and the Development of Continental Margins 72
- Subduction and Island Arcs 83

MANTLE ADVECTION AND CRUSTAL EVOLUTION 88

RIFTS AND STRATIFORM AND STRATABOUND ORE DEPOSITS 98

ARCHEAN NICKEL DEPOSITS 99

EUGEOSYNCLINAL VOLCANOGENIC ORE DEPOSITS 101

- Polymetallic-type Volcanogenic Deposits 104
- Besshi-type Volcanogenic Deposits 112
- Cyprus-type Volcanogenic Deposits 114

VOLCANOSEDIMENTARY DEPOSITS IN AULACOGENS AND TROUGHS 116

The Rosh Pinah Ore Deposit 116
The McArthur River and Mount Isa Ore Deposits 118
The Sulivan Ore Deposit 126

VOLCANOSEDIMENTARY ORE DEPOSITS IN MIOGEOSYNCLINES 129

The Irish Base Metal Deposits 129

STRATABOUND DEPOSITS IN CONTINENTAL YOKED-BASINS 135

The White Pine Copper Deposit 135
The Zambian Copperbelt 140
The Boleo Copper Deposits 144
Italian Pleistocene Uranium Deposits 148
The Athabasca Vein-type Uranium Deposits 150

METAL DEPOSITS IN ACTIVE RIFTS 153

THE ASSOCIATION BETWEEN RIFTS AND MINERALIZATION 159

ACKNOWLEDGEMENTS 164

REFERENCES 165

A GEODYNAMIC MODEL

The geological record indicates that geodynamic processes are characterized by periodicities that vary both in magnitude and duration, although there is evidence that global evolution has passed through major phases of different, non-uniformitarian behaviour. Global evolutionary processes are characterized by developing periods of changing parameters and the loading up of potential energy. These periods are eventually terminated by the partial release of the accumulated energy whereby essentially new situations come into being. Such events are of relatively short duration and are characterized by times of intensified geodynamic movement. The primary source of geodynamic processes occurs within the mantle. The rock record, exposed on the surface of the earth, represents the response of sialic and simatic crust to mantle processes. With an understanding of mantle processes it is possible to interpret the development and evolutionary stages of rifting, magmatism and basin development through time.

MANTLE ADVECTION : A MODEL OF MANTLE PROCESSES

The driving forces of the geological evolution of the globe can be subdivided into nuclear forces and forces of mass inertia. The forces of mass inertia, which are initiated by the gravity field of earth and the rotative inertia of the geoid, dominate processes on a macro-scale, while the interparticle nuclear forces and associated physico-chemical processes are active on a micro-scale. The transformation of rotational inertia into heat along the interface between the inner core and outer mantle has been suggested as a possible energy source for the geodynamic processes of the earth (Van Bremmelen, 1976). An argument for a much higher viscosity in the lower mantle compared to that in the upper mantle has been used to explain the discrepancy between the ellipticity of the earth derived from satellite observations and that expected from hydrostatic theory (Runcorn, 1972). Because the applied stresses are small and of short period, seismic observations can almost entirely be explained by assuming classical elasticity holds everywhere in the mantle. Seismology however, can give little direct information concerning long term behaviour of the mantle involving strain rates of the order of 10^{-15}–10^{-17}/sec (Runcorn, 1972).

Shearing stresses due to frictional action at the core-mantle interface would cause the solid mantle to eventually relax by thermal agitation to the state of lowest internal energy (Rucorn, 1972). This idea has some support from seismic observations which have established the presence of a transitional zone at the core-mantle interface, approximately 450km thick (Van Bremmelen, 1976). The frictional heat produced in this transition zone might be sufficient to drive the geodynamo by thermal convection, while the earths lower mantle might act as the cooling envelope for the geodynamo by removing the excess heat by thermal advection. The thermal energy generated by friction on the core-mantle interface, in addition to the heat generated by the decay of radioactive elements disseminated through the mantle, might be sufficient to change dense minerals into less dense minerals, or to start partial fusion. A transition from spinel-type to olivine-type $(Mg, Fe)_2SiO_4$ results in a decrease in density due to a 10% increase in volume (Ramberg, 1971). Eutectic melting of peridotite would result in a reduction in the viscosity as well as the density of the substratum. The presence of liquid basaltic inclusions or films, occupying approximately 15% of the total volume of the solid peridotite as a "primary basaltic emulsion" would result in a density difference of approximately $0,1\ g/cm^3$ (Belousov, 1971). This decrease in density would be sufficient to set up a state of mechanical instability in response to the development of an inverted density layer.

Tozer (in Runcorn, 1972) argues that the theory of viscous convection is the most general approach to the transport of heat, while the theory of conduction is a special case of the general rheology of solids. He showed that heat transport by advection would keep the temperature of planetary interiors to about half of their melting point and that this temperature is not influenced by the distribution of radioactivity or the initial temperature of the planet. A model for advective rise in the mantle should be thought of as involving a mass whose density is less than the surrounding material because of a different physical state, or different chemical composition and not only due to a higher temperature as in the case of a homogeneous thermal convection system. Motion in the mantle would occur because the less dense material would rise and the denser material of the overlying strata would subside. These motions are similar to those that arise in convection but in so far as the inversion of material is not complete, because the lighter material rises and remains on top, while the denser material descends and remains below, it is more correctly termed advection (Belousov, 1971).

Thermal advection is natures way of turning planetary thermal energy into motion by the action of gravity on density differences. One significant characteristic of low density layers is that their tendency to rise through the overburden increases rapidly with the thickness of the layer. This mechanical instability would initiate waves that would ascend with a velocity that is in effect proportional to the square of the thickness of the layer (Ramberg, 1971). This means that the process would be episodic, as it is only after the low density layer has grown to an appreciable thickness that it would bulge into waves and ascend, eventually leaving only traces of the low density phase behind at the original level (Fig. 1). At this level a new low density layer would form by further phase change sustained by the continuous release of thermal energy. When the layer acquires sufficient thickness a new episode of rise would occur with the overturn of the unstable density stratification (Ramberg, 1971).

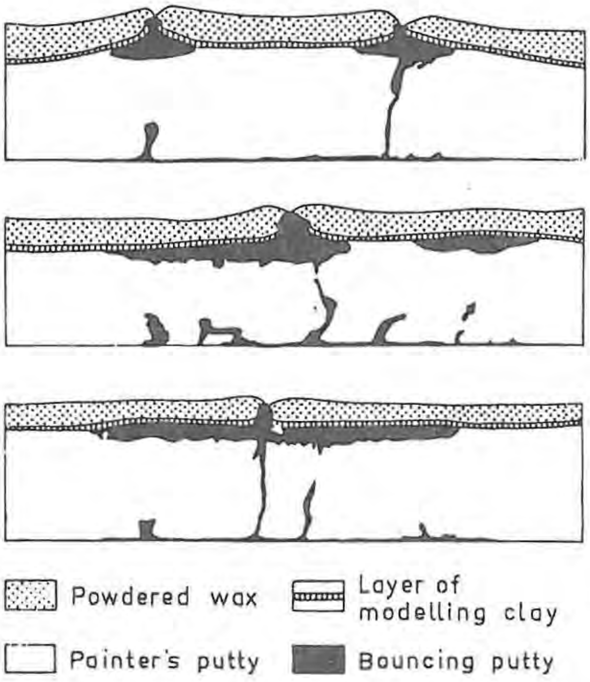
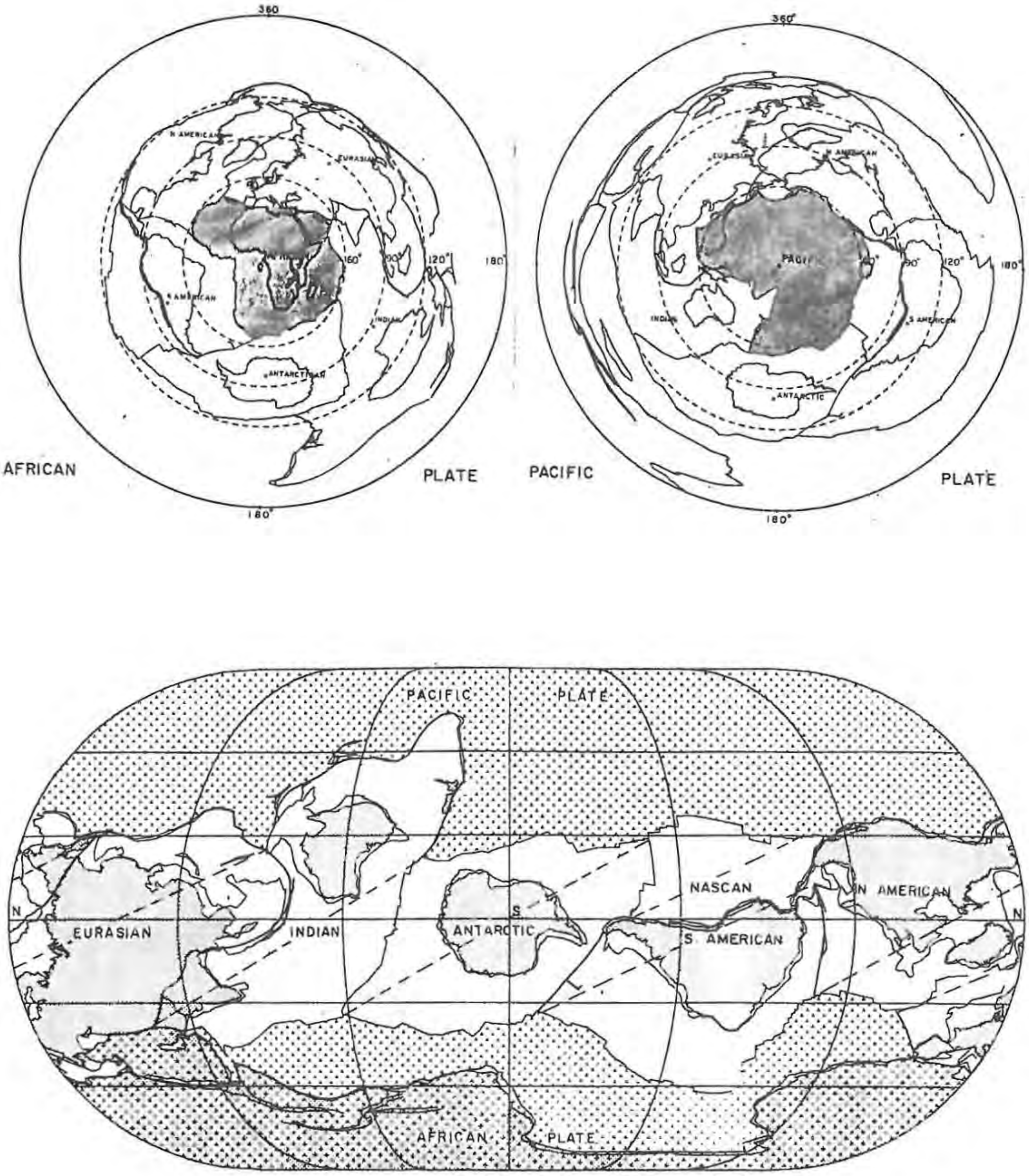


FIGURE 1: Profiles through a scale model, run for 8 min. at 1000g to simulate crustal processes, illustrating the development of a mantle diapir from a basal layer of low density bouncing putty. Note that only traces of the low density phase are left behind at the original level (from Ramberg, 1971).

Seismic probing shows that at the present stage of the earth's history there are no thick global shells or large bodies consisting chiefly of molten material. The general tendency is for density to increase with depth and if an inverted density stratification occurs, the abnormal density layers must be relatively thin compared to the whole mantle (of the order of 10km) (Ramberg, 1971).

The development of salt domes and many granitoid domes is often due to the presence of an inverted density stratification, particularly since rock salt is the least dense of consolidated sediments and basement granitoid gneisses are often less dense than most metamorphosed sediments and lavas of non-granitic composition that are present in geosynclines. The difference between these features and mantle advection is that the continuous release of heat and the progressive development of a low density layer in the lower mantle, together with the eventual initiation of rise, makes the latter episodic. In the process of advection and the absence of any mantle inhomogeneities, circular or polygonal cells would be expected to form in the mantle (Runcorn, 1972).

The regularity of the present ocean-continent distribution is thought to be evidence of a mantle-wide advective system. The remarkable asymmetry of the distribution of the oceans and continent, in which only 5% of the continents are antipodal to the continents, is attributed to the presence of an advective system (Rucorn, 1972). The present-day African and Pacific Plates are antipodal quasi-circular plates that are separated by a ring of quasi-eliptical plates (Fig. 2) (Kanasewich et al, 1978). The topography of the earth, by taking the height of the continental surface above sea level as positive and the depth of the ocean floor as negative, can be expressed by a spherical harmonic series. Vening Meinesz (in Rucorn, 1972) showed that the dominant harmonics of the earth's topography are of the first, third, fourth and fifth degree. An advective current with harmonics of the first degree in an early stage of the earth's history has been suggested as the cause of the concentration of the continents into the one hemisphere as the Pangea Super-continent. The absence of continents in the Pacific hemisphere may be a relic of this early distribution. He also pointed out that on theoretical grounds the convection (or advection) pattern in an aspherical shell of mantle dimensions should be of the third, fourth and fifth degrees. One of the possible causes of changes within such a convection system through time is



PRESENT - 0 Ma

FIGURE 2 (A): Azimuthal-equidistant projections centred on the African Plate and its antipodes in the Pacific Plate showing the geometry of the two quasi-circular plates that both have a radius of 60°.

(B): An Eckert projection showing a ring of quasi-elliptical plates that lie at 90° from the centre of the African and Pacific Plates. Plates are defined by the dashed lines from an African triple junction to a Pacific triple junction (from Kanasewich, et al, 1978).

speculated as being due to the growth of the earth's core by the progressive segregation of the more denser iron and silicate planetisimals from which the earth accreted. The gravitational energy released by the progressive separation of the core through time is thought to be roughly twice as great as the energy produced by radioactivity over the earth's life (Runcorn, 1972).

World-wide periods of enhanced tectonic activity illustrated by the ages of igneous and metamorphic rocks on the cratons, which cluster about 2600my, 1800my and 1000my, could be due to the progressive change in the advective pattern from the first degree harmonics to the second, third and the fourth degree harmonics. In the Late Palaeozoic aleomagnetic data suggests that Eurasia and North America were joined together as Laurasia at low latitudes, while Africa, South America, India, Antarctica and Australia were grouped together around the south pole as Gondwanaland. Significantly the continental blocks were grouped in a simpler pattern, which can be described by harmonics of a lower degree, than the present pattern. The drastic changes in the forces on the continental blocks that took place at approximately 200my, and led to the breakup of Luarasia and Gondwanaland can be best understood by the instability inherent in a "fluid" convection pattern. The former pattern of convection might have been one in which a fourth degree harmonic predominated while the present pattern is one with a strong fifth degree harmonic (See Fig. 2B). Continental drift as a result looses its enigmatic character as a unique and drastic geodynamic change, and becomes merely the latest of four lengthly episodes of crustal upheaval (Runcorn, 1972).

Lenticular, or mushroom-shaped zones of anomalous mantle material are believed to exist below the Mid-Atlantic Ridge (Fig. 3.),the Red Sea and the Rio Grande Rift (Fig. 4). Geophysical studies below the Rio Grande Rift indicate that there is a marked variation in crust and mantle seismic velocities and that the continental crust is thinner beneath the rift. A coincident negative Bouguer anomaly indicates the presence of a negative density contrast in the upper-mantle (Bridwell, 1978). A mantle diapir is considered to be the principal cause of high heat flow and reduced viscosity beneath the rift.

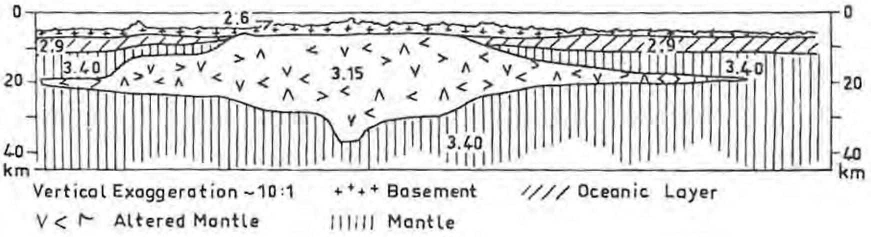


FIGURE 3: Profile across the Mid-Atlantic Ridge according to gravimetric and seismic observations illustrating the presence of a low density mantle diapir at the mantle-lithosphere interface (from Ramberg, 1971).

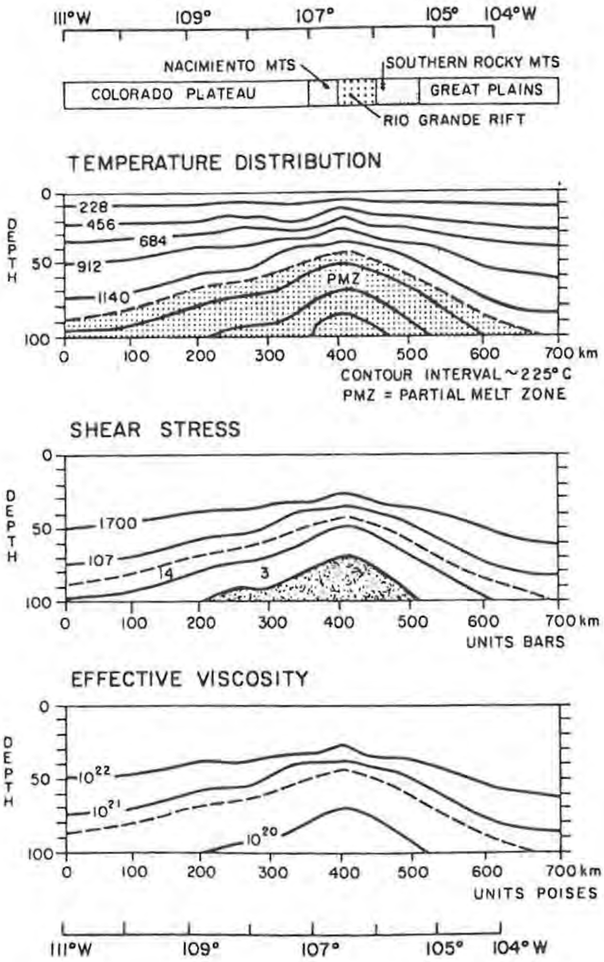


FIGURE 4: The temperature distribution and the variation in shear stress and effective viscosity associated with the presence of a mantle diapir beneath the Rio Grande Rift. The mantle diapir, or zone of partial melt, is associated with higher temperatures, significantly reduced shear stress and a pronounced viscosity low (from Bridwell, 1978).

Scale models, when scaled up to natural dimensions, have excluded the possibility that a mantle diapir can be as fluid as a silicate melt. All known silicate melts are too fluid to form bulky mushroom-shaped bodies but would rather penetrate the overburden as dykes or sills (Ramberg, 1971). Ramberg's experiments suggest that upward migrating diapirs, which originate from domical ridges in the source layer, would become detached from the source layer and change progressively from lenticular to circular sections, finally increasing in diameter and mushrooming into shallow levels of the mantle, usually at the base of the lithosphere or crust. Advective currents have a tendency to spread out under gravity as the confining pressure decreases and due to resistance of the overlying lithospheric roof to deformation. As the mantle diapir rises, a decrease in pressure would be expected to cause further melting to take place within the rising plastic crystalline mass. The buoyant, less viscous melts would penetrate fractures and erupt as lavas on the surface of the crust while the semi-crystalline viscous mushroom-shaped mantle diapir would continue to spread laterally below the crust (Ramberg, 1971). The forces generated by vertical uplift associated with a buoyant mantle diapir, together with the lateral motion associated with the spreading of the diapir beneath the lithosphere would be sufficient to cause horizontal extension and continental drift. The theory of mantle advection therefore explains the gradual uniform movements of the continents and ocean floors that have occured during the Mesozoic and Cainozoic following the breakup of Gondwanaland and Laurasia. Magnetic evidence shows that the motions have been relatively uniform (1-10cm/year) and that the mean flow vectors change only over distances of the order of the earth's radius, which suggests that advective flow occurs in a cellular pattern (Runcorn, 1972).

The coincidence of major plate tectonic changes with changes of the geomagnetic reversal frequency suggests that processes in the upper mantle and the core are somehow linked (Vogt, 1975). The parallelism of volcanic island and seamount chains in the Pacific Ocean and the continuity and uniform progression of ages of the volcanoes to the North-west along the Hawaii Islands-Emperor Seamount chain, suggests that the Pacific Plate has moved progressively over four fixed mantle "hot spots" at a rate of ±10cm/year (Fig. 5). These volcanic island-seamount chains are characterized by a distinctive kink that corresponds to a major change in direction of the Pacific Plate-mantle motion between 42-44my (Morgan, 1972). The Mendocino Fracture Zone also changes azimuth at ±42my indicating that a re-orientation of the Pacific-Faralon Plates was coeval with the Hawaii-Emperor Bend (Vogt, 1975). The only major change in geomagnetic reversal frequency is the last 70my correlates with the age of the Hawaii-Emperor Bend (Fig. 6). The 45my isochron on the Eurasian Plate south of the Reykjanes Ridge marks a change in direction of plate motion between Greenland and Europe, as well as a change in geomagnetic reversal frequency. At the same time numerous small transform faults were generated apparently in response to a change in spreading direction (Fig. 7). The above two examples illustrate the synchronization of geomagnetic reversals with major changes in lithospheric plate motions. Similar relationships indicate that changes in the geomagnetic reversal frequency correspond to major plate tectonic changes at about 70-80my and 110-120my (Vogt, 1975).

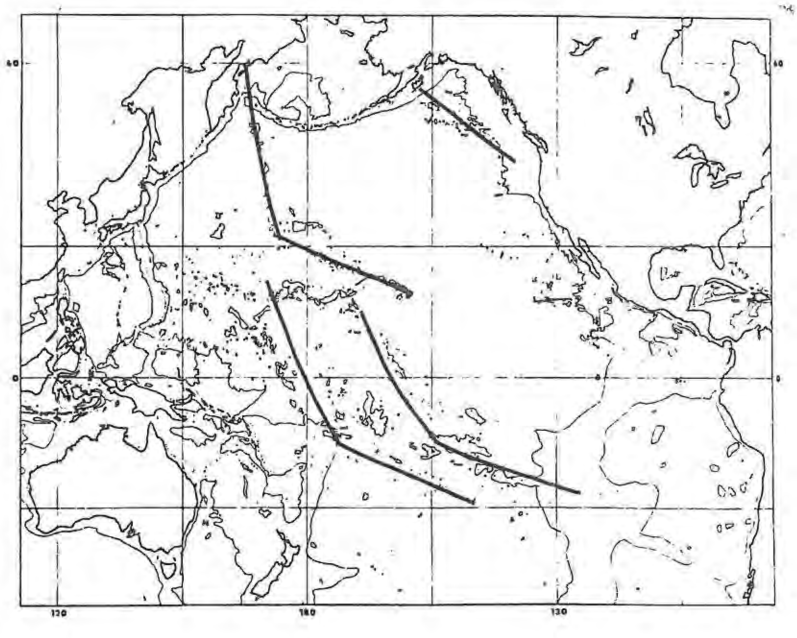


FIGURE 5: Four groups of volcanic island-seamount chains in the Pacific Ocean (solid lines), formed by the progressive drift of the Pacific Plate over four fixed mantle "hot spots", that are characterized by a distinctive kink which corresponds to a change in Pacific Plate-Mantle motion at 42-44my (from Morgan, 1972).

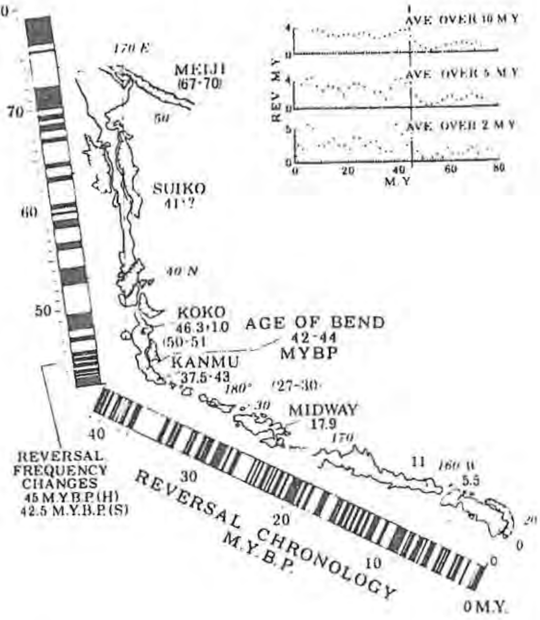


FIGURE 6: Age dates along the Hawaii-Emperor Chain and reversal chronology. Smoothed reversal frequency indicates that the time of major frequency change corresponds closely to the age of the Hawaii-Emperor "Bend" (from Vogt, 1975).

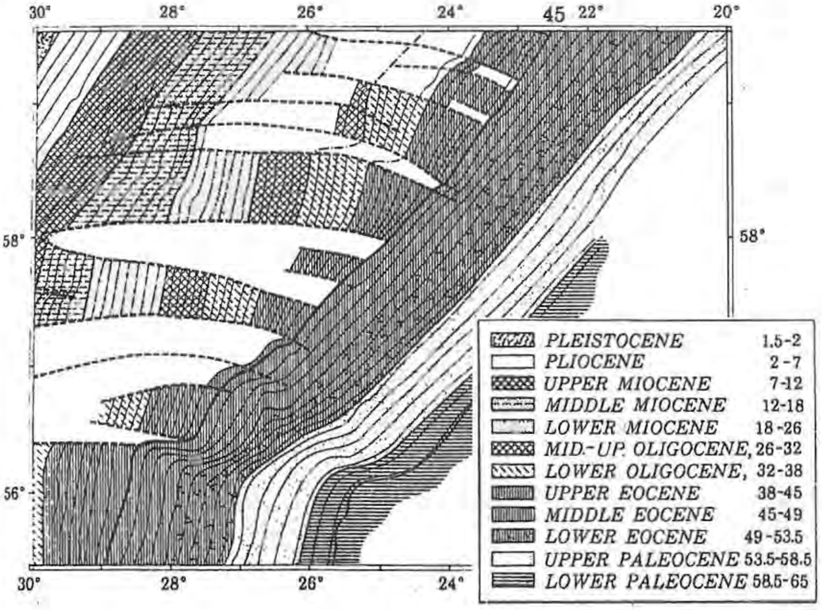


FIGURE 7: Age contours between the Reykjanes Ridge Crest (upper left) and the Rockall-Hatton Bank showing a major change in spreading direction, reversal frequency and the formation of small transform faults at about 45my (from Vogt, 1975).

The geomagnetic field is thought to originate in the core, although the exact mechanisms are still debated. It has been suggested that the sign of the geomagnetic dipole depends on quite minor features of core motions. One way geomagnetic reversals might relate to core "fluid" motions is that at any given time cyclonic convection cells are randomly distributed throughout the core. Reversals of the dipole field would occur whenever these cyclones, through random processes, arrive at certain critical configurations. If some mantle advection geometries produced core-mantle interface conditions more favourable to critical configurations of core cyclones, then reversals would be more frequent whenever mantle advection happens to have those geometries (Vogt, 1975). Any changes in the mantle advection pattern or intensity might therefore be expected to alter the boundary conditions at the core-mantle interface and thereby change the reversal frequency or other properties of the geomagnetic field.

The theory of mantle advection involves the periodic generation of mantle diapirs in response to the continuous generation of frictional thermal energy, possibly on the core-mantle interface. Mantle diapirs move through the mantle in response to mass inertia, the action of gravity and the rotative inertia of the geoid on density differences. Such a model provides the basis for the driving force for geodynamic processes by the interaction of the buoyant mantle diapirs with the lithosphere and sialic crust.

CRUSTAL RESPONSES TO MANTLE ADVECTION

Primary forces in the earth set up a state of stress and produce disturbances of great magnitude while secondary forces tend to bring about a partial or complete restoration of equilibrium and so produce the observed distortions. The diapiric rise of a mantle diapir is confined to some extent by the resistance of the less viscous lithosphere and continental crust to deformation. The upward pressure of the ductile rising column is opposed by the downward pressure of the elastic arched-up roof which causes the ascending current to be squeezed sideways to form a mushroom-shaped structure (Ramberg, 1971). The excess pressure that develops in response to the rise of a mushroom-shaped mantle diapir of partially molten mantle material beneath the lithosphere would produce an elliptical-shaped uplift at the surface. In response to this vertical uplift rifting will occur in the continental crust when the shearing stress exceeds the strength of the sialic material. Typically a graben, or half graben would be expected to bisect the elevated crustal dome. The graben often widens into a fan-shaped trough towards the ends of the long axis of the elliptical uplift. Normal faults tend to develop on the flanks of the uplift parallel to the central graben (Withjack, 1969). The hypothesis of the formation of "triple junctions" (see Burke and Dewey, 1973), lacks the support of any theoretical or experimental data and in nature the postulated 120^0 angular difference is rarely realized (Bahat, 1979).

A mathematical model of the crustal stress pattern within a homogeneous thick plate has been used to predict the fault patterns associated with vertical crustal uplift alone and a combination of crustal uplift and regional horizontal extension. It was found that in response to domal uplift, local tension at the crest of the uplift would promote the formation of a central graben (Fig. 8). A superimposed regional horizontal tension was found to eliminate the large compressive stresses and potential strike-slip and thrust faults that would develop on the uplift periphery in response to domal uplift alone. The regional horizontal tension would promote normal faulting on the flanks of the dome (Withjack, 1979). The model predicted a wide zone of normal faulting away from the crest of the uplift and predicted that towards the ends of the long axis of the elliptical uplift, normal faults would radiate outwards from the uplift crest to produce a fan-shaped trough at the terminations of the uplift (Fig. 8C). The model assumed that the continental crust is homogeneous. However, zones of weakness exist in the crust so that fault orientations adjacent to rift-bounded grabens may reflect these inhomogeneities, rather than the state of stress in the crust. Faults that form during the rifting process introduce new inhomogeneities into the crust and therefore modify the state of stress in the adjacent rocks so that secondary faulting may occur. Furthermore, the modification of the stress state adjacent to an early fault zone may cause propagation of those early faults (Withjack, 1979).

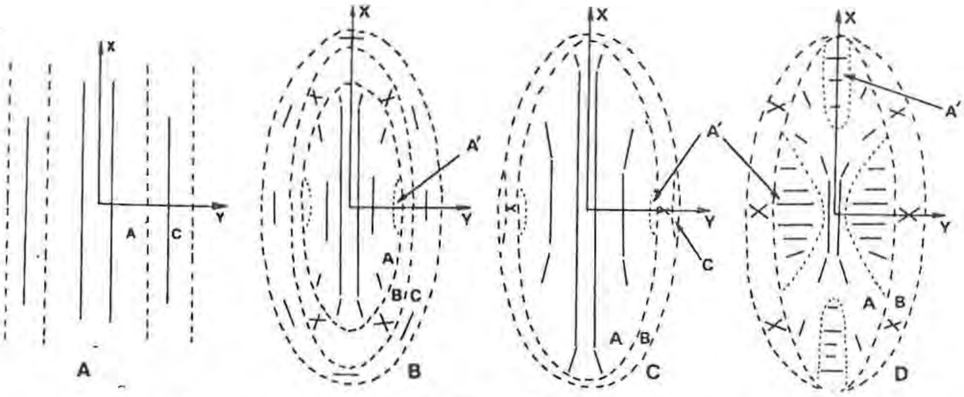


FIGURE 8: The predicted fault patterns for the domal uplift mechanism of rift initiation: (A) fault pattern associated with a linear uplift with no superposed tensions; (B) fault pattern associated with a domal uplift with a length-width ratio of 8:1 and no superposed tensions; (C) fault pattern with superposed tensions of 2 along the Y-direction and 1 along the X-direction; (D) fault pattern with superposed tensions of 1 in the Y-direction and 2 in the X-direction. Zones A, B and C contain normal faults, normal faults trending parallel to the Y-axis, strike slip and thrust faults, respectively. The superposed tensions associated with a spreading mantle diapir would best conform to case (C) and significantly this fault pattern is typical of rifts developed in domal uplifts (after Withjack, 1979).

The process of fracturing causes an instantaneous and drastic alteration in the pre-existing stress system. The principal result would be a drastic diminution of the stress in the neighbourhood of the origin of the fracture, while further away the initial stress distribution would remain essentially unaltered. The first fault thus provides local relief in the most intensely stressed portion of the block. After faulting occurred the stress system would continue to build up, and additional portions of the block would gradually reach and exceed the limit of brittle strength. Renewed faulting would then occur some distance away from the first fracture in a zone where the stress relief was negligible. Even though the conditions are no longer exactly the same, the new fracture would still conform closely to the original stress pattern. The later fault would most probably belong to the same set as the initial one, as a secondary fracture utilizing the conjugate direction would project into the protective zone of low stress surrounding the initial or preceeding fault. The local relief of stress around the early fractures would gradually disappear, due to the tendancy of the original stress system to re-establish itself. This would then lead to renewed faulting in already fractured segments (Hafner, 1951). A domal uplift would therefore be expected to produce a series of fairly evenly-spaced normal faults that would be periodically reactivated.

In conjunction to an upward pressure being exerted on the lithosphere and crust by a buoyant mantle diapir it is probable that viscous drag, with associated shearing stresses, would exist on the bottom of the lithosphere as the diapir progressively flattened out. The vertical pressure associated with a mantle diapir would gradually decrease from a maximum value at the centre to zero at both ends, while the bottom shear stresses would increase from the centre towards the extremities of the diapir. Therefore a laterally variable, approximately sinusoidal, vertical boundary stress acting on the base of a lithospheric block would most likely have a corresponding sinusoidal shear-stress component that will be 90^o out of phase (Hafner, 1951). Certain "balanced" ratios of the components of pure drag and pure differential vertical uplift would cause a supplementary horizontal tensional stress to develop in the zone subjected to the increased upward pressure. In response to the gradual build-up of a stress system of this type, instability, with resulting faulting, would be first reached in a wide, but relatively thin layer below the surface (Fig. 9). With continued intensification of the primary stress this zone would gradually expand in depth and to a lesser degree sideways. Very high primary stresses cause the zone of instability to extend the full depth of the crustal or lithospheric block, except for the deeper central portion where the maximum shear stress would still be below the crustal strength. However, as the wavelength of the primary stress field increases and the ratio of the shearing stress to vertical stress decreases, the zone of instability would extend through the whole block and reduce the relative proportion of stable to unstable segments (Fig. 9B) (Hafner, 1951).

It is interesting to note at this stage that zones of variable subsidence, due to descending mantle material, would be subjected to a corresponding compressive stress (Fig. 9B). The boundary shear stresses on the base of the crust would set up a horizontal compression which would produce thrust faults near the surface of the crust. If the lateral gradient of the superimposed horizontal pressure is small, approximately half the vertical pressure gradient due to the weight of the crust, the potential zone of faulting would be limited to a thin wedge below the surface in which numerous shallow thrusts would be expected to occur. If the gradient is sufficiently large, about equal to the vertical gradient, the thrust faults might penetrate to great depths but would then be confined to a comparatively narrow zone. The inclination of the resulting thrust surfaces would also be expected to diminish rapidly with depth (Hafner, 1951). The boundary zones between the belts of extension and compression are characterized by the absence of a superimposed horizontal stress and

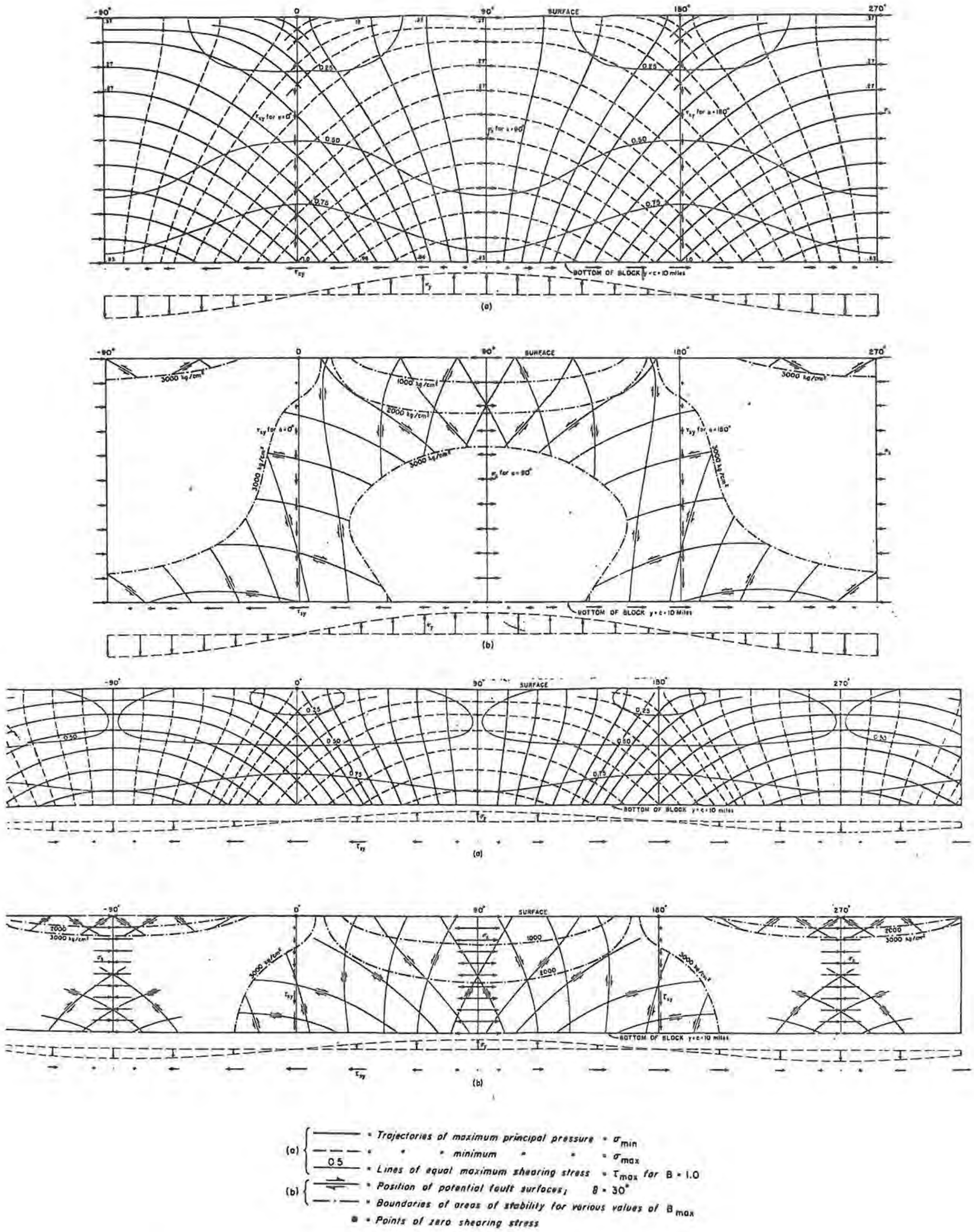


FIGURE 9: The state of stress and associated fault patterns in a crustal block in response to a supplementary stress system, consisting of a variable vertical and shearing stress along the base of the block, generated by a mantle diapir. (A) Equal variable vertical stresses and shearing stresses, 90° out of phase; (B) Vertical stress half the shearing stress, 90° out of phase, with a wavelength double that of (A). (A and B on different scales). The arrows illustrate the relative magnitudes of the different stresses. The boundaries of the different areas of stability correspond to the maximum value of the uplifting force at the base of the crustal block. The gradual upward rise of a mantle diapir causes the zones of faulting to penetrate deeper into the crust, while the gradual spreading of mantle diapir (from A to B) and increase in wavelength causes a change in the relative proportions of stable and unstable zones (from Hafner, 1951).

by the presence of maximum shear stress components. This causes a 45° rotation of the stress trajectories, which in turn lead to a pronounced change in the attitudes of the fault surfaces. Although normal faulting occurs over the central uplifted portion, towards the margins one of the two sets would gradually change to very steep, vertical and finally overturned attitudes, while the complementary, but rarely realized set of normal faults would assume very low inclinations. As a result, the nearly vertical normal faults or major rifts, that are frequently characterized by differential vertical uplifts in tectonic provinces can be explained as primary features of such stress systems (Hafner, 1951). The above discussion holds true for the stress distribution in a homogeneous crust. Any existing fault and fracture systems would be expected to influence the superimposed stress distribution. A radially spreading mushroom-shaped mantle diapir would be expected to reactivate these old linears. Should the crustal block be fully fractured additional propagation of the fractures would occur laterally.

A detailed examination of the stresses systems developed in the models enables one to predict the structural implications of the rise of a buoyant mantle diapir, it's slow lateral spreading and eventual decay with the downward sinking of depleted mantle material. Initial uplift associated with a narrow confined diapir would generate a period of normal faulting in a zone close to surface. This would be followed by the generation of marginal steep penetrating rifts that would extend the crust. Progressive lateral spreading of the diapir would cause the zone of the normal faulting to penetrate through the whole crust and cause extension and thinning of the crust. Thinning of the sialic crust would also initiate isostatic subsidence as the Moho boundary ascended. Eventual decay of a mantle diapir and subsidence of depleted mantle material would generate thrust faulting in a thin wedge below the surface, and possibly at very high stresses, deep crustal thrusts confined to a narrow zone.

MAGMATIC ACTIVITY : A RESPONSE TO MANTLE ADVECTION

A mantle diapir can be considered to consist essentially of a semi-crystalline mass of peridotite that contains intra-granular films of basaltic partial melt. As mantle diapir rises, a reduction of pressure would cause the de-emulsification of the "primary magmatic emulsion". The films of partial melt on the surfaces of adjacent crystals in the magmatic emulsion would segregate into large magma aggregates. Shearing appears to be an essential part of a mechanism for the segregation of basaltic magmas by analogy with the formation of water bubbles in glaciers, their subsequent coalescence and upward migration. Such shear melting may be important in not only explaining how melts are produced in the asthenosphere, but why they are produced episodically (Pitcher, 1979). As the basaltic liquid combined into even larger aggregates these magma diapirs would increasingly outpace the residual mantle material during their upward movement in response to a significant density difference between that of the magma ($\pm 2,6 g/cm^3$) and the residual material ($\pm 3,2 g/cm^3$). A similar mechanism of magma aggregation due to deformation and pressure relaxation of a crystalline mass has been suggested for the generation of granitic "gneiss-domes", some of which show structural indications of having gone through a magmatic stage in their central part (Fig. 10) (Talbot, 1971).

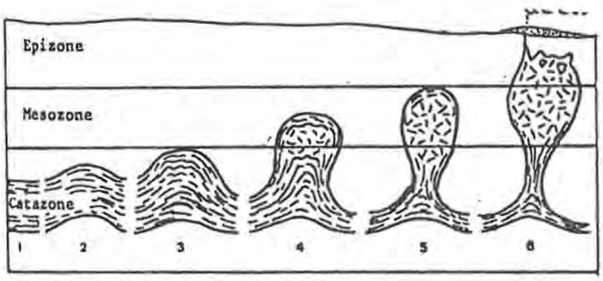


FIGURE 10: A schematic diagram illustrating the time sequence of anatectic granite formation due to the rise of a gravity-driven diapir generated in a granite-gneiss source layer during orogeny (from Talbot, 1971).

Experiments indicate that all the basaltic magma-types may be obtained by direct melting of peridotitic mantle at various pressures. The chemical equilibrium between a host rock and partial melt primarily concerns the compositions of the phases present and not their relative volumes. In consequence the composition of the different partial melts will depend to a large extent on the pressure, or depth of melting. If the basaltic liquid remained in contact with the residual crystals as the mantle diapir continued to rise, the composition of the liquid would vary as the pressure changed in such a way that the resultant magma would have a composition identical to that of a magma formed by direct partial melting of the mantle at the given depth. It is only when the liquid is isolated and looses contact with the residual crystals that it ceases to depend upon its depth within the mantle (Belousov, 1971). The composition of a basaltic magma therefore depends on the depth or pressure at which it ultimately separated from the crystal mush. Kimberlites and alkali-olivine basalt magmas separate at the greatest mantle depths and at progressively shallower mantle depths high-alumina basalt, olivine thoeliite and quartz-thoeliite basaltic magmas segregate (Fig. 11) (Green and Ringwood, 1967).

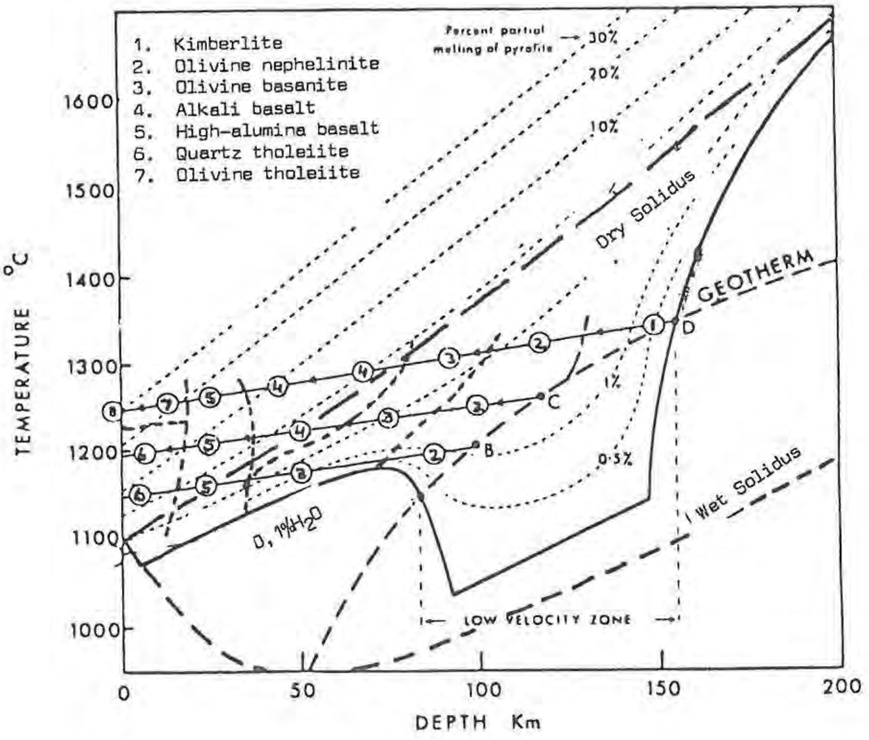


FIGURE 11: Possible relationships between mantle solidus, mantle temperature distribution, degrees of partial melting of pyrolite and the nature of the basaltic magmas produced. The straight lines represent the P-T paths followed by magma diapirs, while the numbers on the lines indicate the magma-types formed by magma segregation at different stages of partial melting (after Green and Ringwood, 1967).

Deep faults, or rifts would promote partial melting by rapid pressure reduction as a result of differential vertical movements. Differential movement on large hinge faults is likely to produce different degrees of pressure reduction and therefore different degrees of partial melting. Zones of shear within these rifts would also facilitate the segregation of partial melts from a "primary magmatic emulsion". These rifts would also provide low pressure zones to which new magma could migrate and therefore magmatism would be focused on and funnelled into these deep taphrogenic fault zones, or rifts. These discontinuities would also be zones of abnormally high heat flow and therefore increased ductility and permeability. Taphrogenic rifts should therefore be considered, from a physical point of view, as being channels of reduced viscosity (Belousov, 1971).

The effect of the interaction of a pluton and adjacent host rock envelope depends on the viscosity contrast between the buoyant diapir and the host medium. Low viscosity contrasts permit plutonic magma chambers to exist, while large contrasts leads to cauldron-type collapse in the upper parts of the crust and subsequent extrusion of the magmas (Pitcher, 1979). The viscosity of the magma itself, is however, important in controlling internal processes within a pluton; such as viscous flow, heat transfer and crystal settling. The basaltic magma diapirs that separate from mantle diapirs could either migrate through the sialic crust along major taphrogenic rifts, but would however, be confined to a large extent by structurally homogeneous continental crust. In the latter situation the magma diapirs would transfer heat into the crust and migrate upwards by means of melting and assimilation of the rocks making up the sialic continental crust.

Detailed work on the Coastal Batholith in Peru indicates that there is a genetic relationship between the basic plutonic rocks, mainly gabbros, and the more predominant granitoids; tonalites, granodiorites and granites. The granitoid rocks define a classic calc-alkaline trend, which is true at any level of detail, from the overall sequence of super-units in a batholith to single-pulse plutons, that are the result of in situ differentiation (Pitcher, 1978). On the AFM diagram the granitoids define a calc-alkaline trend which intersects the less defined tholeiitic trend of the more tightly grouped gabbroic rocks (Fig. 12A) (Pitcher, 1978). Detailed geochemistry has indicated that the gabbroic rocks have a high-alumina basaltic chemistry with primitive rare earth element characteristics, indicating a fairly deep mantle origin. When the relative volumes of the different magma-types are considered, it is found that the mafic rocks decrease in volume while the felsic rocks increase in volume with time, so that there is an overall mafic to felsic trend (Fig. 12B). Although the magmatism in the Coastal Batholith was episodic in nature, each super-unit does not represent different fractionated pulses but rather separate generations of new magma (Fig. 12B) (Pitcher, 1978). The early gabbros are interpreted as being of sub-crustal origin while the progressive evolution towards true granites suggests an increasing crustal contribution with time. The basaltic magmas, in their role as precursors

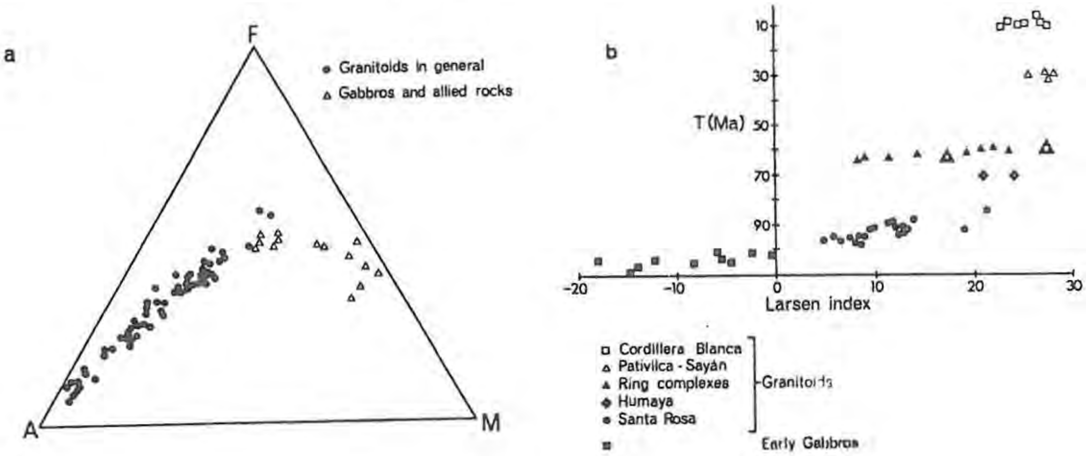


FIGURE 12 (A): AFM plot of the compositions of the early gabbros and granitoids from four super-units in the Coastal Batholith of Peru.
(B): The compositions of the gabbros and granitoids plotted as the Larsen Index against the K-Ar ages of the different phases (from Pitcher, 1978).

to the granitoids, are thought to provide the triggering mechanism for the whole process of batholith formation (Pitcher, 1979). Such a model that envisages contributions from both the mantle and crust clearly implies that the mantle-derived basaltic magmas would provide large quantities of heat for the partial melting of lower continental crustal rocks. These magmas would also be in chemical disequilibrium with the lower crustal rocks and would therefore assimilate sialic material on the contacts to produce a continuous series of magmas of different chemical compositions. The composition of the magma would depend on the initial composition of the basaltic magma and the extent of assimilation. The resultant calc-alkaline magmas would have lost most of the chemical characteristics of the original basaltic magmas, except for those elements that partition preferentially into the melt, particularly copper.

The continued transfer of heat from mantle diapir to the lower continental crust would move the temperatures in the continental crust closer to the liquidus. The breakdown of muscovite at $\pm 710^{0}$C, of biotite at $\pm 820^{0}$C and of hornblende at $\pm 860^{0}$C, depending on the activity of the water, is expected to produce 0,5%, 1,1% and 0,7% of hydrous melt per mineral percent respectively (Burnham, 1979). The continued interaction of basaltic magma diapirs with the continental crust would therefore produce calc-alkaline magmas that with time would progressively contain a higher proportion of sialic material. As a result anhydrous basaltic magmas rising from the upper mantle into the continental crust could generate, by anatexis and assimilation, large quantities of H_2O-bearing melts that would vary in composition from diorite to granite and contain between 3-9% H_2O (Burnham, 1979).

Large batholithic volumes of granitic magmas cannot be attributed to partial melting during high-grade metamorphism as often the peak of regional metamorphism and the production of granitic magmas are considerably divorced in time (Pitcher, 1979). The production of granitoid calc-alkaline magmas in great volumes seems to require a more localized re-melting of lower continental crust material by the intervention of heat and water-bearing magmas derived from sub-crustal sources. Such a model envisaging contributions from both mantle and crust clearly implies that the nature of the crust will play a decisive role in determining the type and relative abundance of the magma-types (Pitcher, 1979). If the basaltic magmas acted just as a heat source without reacting with the lower continental crust, significant quantities of granitic magmas could be generated. However, in order for water-saturated granitic melts to reach surface the final temperature should exceed 900°C because melts at lower temperatures would soon re-intersect the solidus curve during ascent (Winkler, 1974). This is probably the main reason why granites are the dominant plutonic rocks and why a number of metamorphic anatectic melts are often situated close to their source rocks.

At geologically acceptable temperatures, melts more felsic than a granodiorite can be produced and mobilized by crustal anatectic melting. Tonalite and granodiorite melts are, however, comparatively dry. This places severe restraints on genetic models, as the fluidity of calc-alkaline melts decreases rapidly as the water content falls below 2% wt. In consequence tonalite and granodiorite magmas cannot be produced without the interaction of mantle-derived magmas. The most important effect of the water content is its effect on the liquidus-solidus relationship Wet calc-alkaline magmas would be expected to freeze by a decrease of pressure alone, despite the heat of crystallization. The wetter the magma the more likely it would freeze before reaching the surface. It might be predicted that the more granitic the magma the more likely it is to be in the form of a crystal mush. This could explain why granitoid rocks are the dominant plutonic rocks, since the liquidus-solidus relationships in basaltic magmas do not introduce a pressure barrier to the same extent. This is the main reason why the volume relationships in batholiths are the reverse of that expected from the melting process. Only the drier, higher-temperature melts, and therefore less silicic magmas can intrude through to the low pressure regions of the upper crust to form thick basaltic to andesitic volcanic piles on the surface (Pitcher, 1979).

Relatively hot and dry calc-alkaline magmas, derived at least in part from the mantle, which are channelled and intruded relatively rapidly along taphrogenic rifts within a rigid crust would either be extruded on the surface or would fill cauldron-type magma chambers. Such hot magmas might have sufficiently low viscosities when isolated in the magma chambers to permit in situ differentiation to produce volcanic derivatives. The passage of calc-alkaline magmas would also be greatly facilitated by the creation of a narrow "heat plume", or zone of increased ductility, in response to the migration of basaltic magmas along major taphrogenic rifts within a relatively cool crust. Magmas rising in a warm ductile crust above a broad "heat plume" of a mantle diapir would more likely form globular bodies that would expand diapirically as they rose slowly through the crust. The calc-alkaline magmas in such diapirs are likely to be viscous, due to crystallization during an extended period of ascent, so that the coeval extrusion of magma is effectively prevented.

Magmas that segregate during the early stages of mantle diapirism would consist mainly of low degree partial melts that separated at great depths. Therefore per-alkaline and alkaline magmas would be associated with the initiation of crustal doming and subsequent rifting. After the initial uplift, the crust above the mantle diapir would subside due to isostatic readjustment in response to the thinning of the sialic crust by horizontal extension associated with the progressive lateral spreading of the mantle diapir. These areas of rapid progressive downwarp would form geosynclinal zones that are characterized by extreme fragmentation and permeability (Belousov, 1971). Beneath the geosynclines the zone of partial melting in the mantle diapir rises to shallow depths due to progressive thinning of the continental crust. This would allow a high degree of partial melting to take place to form extensive amounts of olivine and quartz tholeiitic magmas. The residual peridotite, or dunite that remained after the separation of the basaltic magmas would either sink back with the decaying mantle diapir or might be tectonically incorporated into the lower sialic crust.

Tectonically incorporated peridotite would be serpentinized in response to the absorption of water released during metamorphic dehydration reactions. A significant reduction in temperature and density (from ±3,2gm/cm^3 to ±2,5gm/cm^3) would be associated with a corresponding increase in volume. It is thought that these low temperatures (500°C), low density and therefore mechanically unstable serpentinities would rise diapirically up along fractures within the crust to form alpine-type peridotites (as opposed to ophiolites, which are fragments of oceanic crust) that are characteristic of most geosynclines (Belousov, 1971). The vast volumes of basaltic magmatism erupted onto the surface would represent an insignificant portion of the total volume of basaltic magma diapirs generated in the mantle diapir in the upper mantle. A major proportion of these magma diapirs would utilize slower mechanisms of rise and would either come to halt at various depths below surface to form differentiated sills, or would interact with rocks in the lower crust to form calc-alkaline magmas. The calc-alkaline magmas have a slower rate of ascent and therefore tend to post-date the tholeiitic lavas. The large quantities of basaltic magma diapirs that interact with the continental crust leads to the development of a zone of high heat flow and in consequence, regional metamorphism and local anatectic melting. The nature of the crust also changes progressively from brittle to ductile so that the magmatism changes from rapid extrusive to predominately slow dispiric rise with associated differentiation, assimilation and the development of large late-stage calc-alkaline batholiths.

In contrast to the geosynclinal areas, the stable platform areas away from the mantle diapir are not subjected to crustal thinning, rapid subsidence, high heat flow and regional metamorphism. In the platform areas there is practically no heating and as a result, melting through the continental crust is very difficult so that magmas only rise along taphrogenic rifts. As a zone of partial melting at the extremities of the mantle diapir it is at considerably greater depths below the platforms than below the geosynclines, the magmatism is typically alkali basaltic, basonitic or even kimberlitic. Platform areas are characterized by stable tectonic conditions and as a result, allow in situ differentiation to take place in cauldron-type magma chambers to produce highly fractionated alkali volcanics and subvolcanic ring complexes.

THE GEOLOGICAL EVOLUTION OF THE EARTH

If the theory of mantle advection can be applied to the initiation of rifting, basin development and magmatism, and the subsequent orogeny and metamorphism then this theory must also be able to account for the non-uniformitarian evolution of the earth through time.
The non-uniformitarian behaviour appears to have a periodicity of approximately 800my characterized by cycles of fairly uniform behaviour that were terminated by intense geodynamic upheaval. These periods of geodynamic upheaval correspond to the end of the Archean (±2500my), the end of the Early Proterozoic (±1800my), the end of the Mid Proterozoic (±1000my) and the end of the Palaeozoic. The earth is presently within the Mesozoic-Cainozoic cycle. In order to examine the relationship between geological evolution and mantle advection the major characteristics of each of the different cycles will be examined. The discussion will be illustrated by taking examples from mainly North America, for the only reason that the geological record is fairly complete and that it has been well documented.

THE ARCHEAN

Archean terrains consist of essentially synclinal greenstone belts, of volcanic and sedimentary sequences that are in-folded within extensive areas of ortho and para-granitic-gneisses. The characteristic feature of the Archean terrains are the slightly elongate to rounded granitic domes that have complex folded and foliated internal structures Preserved between these granitic domes are the folded synclinal to oval greenstone belts, characterized by the development of interference fold patterns (Fig. 13) (Salop and Scheinmann, 1969). Remnants of a pre-existing sialic crust have been found to extend back to at least 3800my. These remnants, however, make up a very small proportion of the presently exposed Archean terrains. Two major ages of greenstone belts are known, although it is only on the Rhodesian Craton that this relationship has been clearly established. The older pre-3000my greenstone belts are preserved within the Pilbara Block, and the Kaapvaal and Rhodesian Cratons, while the younger ±2600my greenstone belts are best developed in the Superior Province of Canada, the Yilgarn Block in Australia and within the Rhodesian Craton.

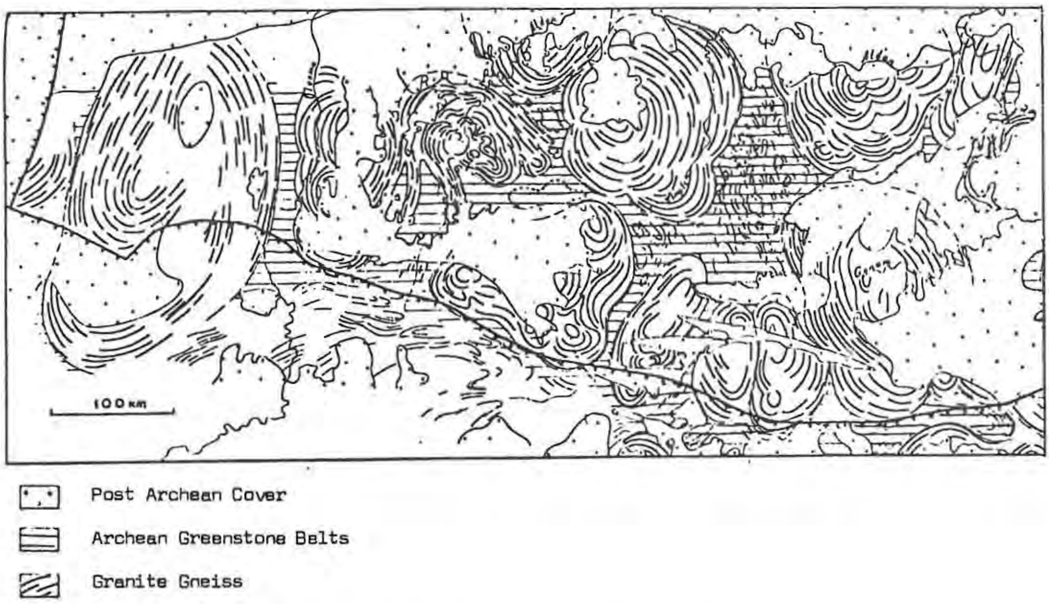


FIGURE 13: Tectonic structures of the Archean terrain in the Aldan Craton of Russia showing the development of large dome-shaped areas of foliated granite-gneiss with complex internal structures. The synclinal to oval greenstone belts between the domes are characterized by a smaller-scale dome and basin structural style. The hatured line marks the boundary between the stable platform area and the Stanovoy Geosyncline during the Proterozoic and illustrates the effect of reworking of the Archean Basement during Proterozoic Orogenies (after Salop and Scheinmann, 1969).

The greenstone Belts consist of extensive domical piles of ultramafic to mafic volcanics, capped by less profuse cyclic calc-alkaline volcanic sequences (Goodwin and Ridler, 1970). The volcanics grade laterally into thick sequences of volcano-clastic greywackes deposited in tectonically active troughs. The characteristic presence of komatiitic volcanics at the base of most major volcanic piles suggests that the geothermal gradients in the Archean were significantly greater than the present geothermal gradients, so that high degree partial melts commonly developed in mantle diapirs. Komatiitic volcanism is preferentially developed adjacent to large taphrogenic rifts, a relationship that is best illustrated in the Thompson Belt in the Superior Province and the Wiluna-Norseman Belt in the Yilgarn Block. The extrusion and intrusion of ultramafic magmas in the Archean appears to be closely related to the presence of significantly steepened thermal gradients, illustrated by the development of telescoped low pressure granulites to greenschist metamorphic patterns. In the Wiluna-Norseman Belt the high-grade metamorphic zones can be related to major taphrogenic rifts, while the lowest grade metamorphic zones are confined to the central parts of the greenstone belts (Fig. 14) (Binns, et al, 1975). Ultramafic magnetism, and associated nickel deposits, are closely related to the high-grade metamorphic domains. This suggests that the metamorphism is associated with the transfer of heat from mantle derived magmas along the major rifts

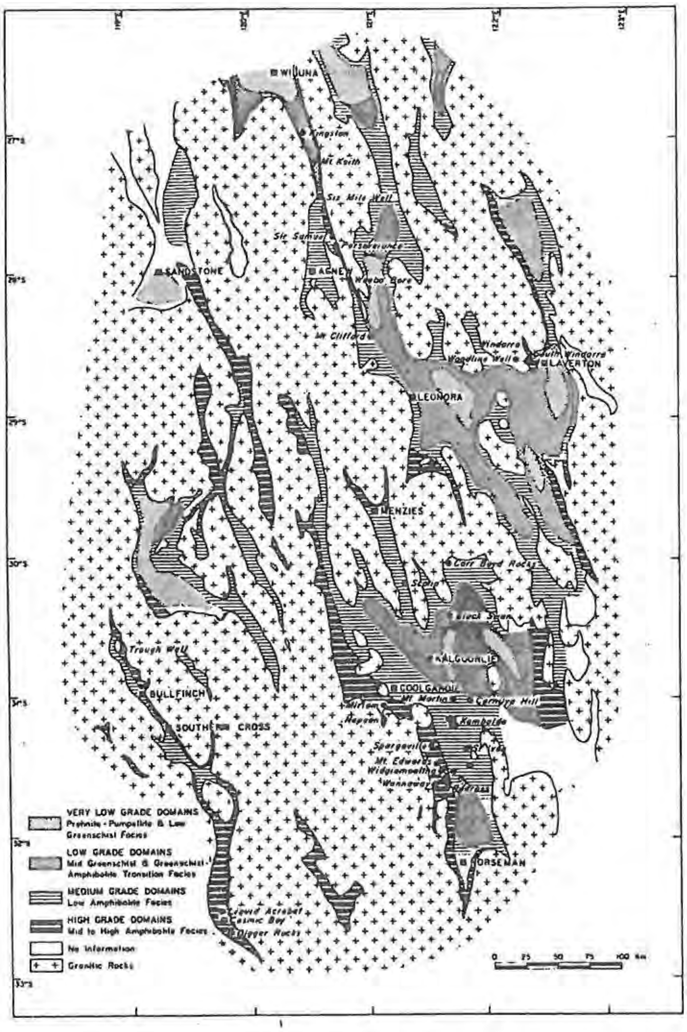


FIGURE 14: Metamorphic map of the eastern Yilgarn Block illustrating the linear distribution of high-grade metamorphic zones and the confinement of low-grade metamorphic zones to the central part of greenstone belts. Ultramafic-hosted nickel deposits (circles) are concentrated in the high-grade zones close to major rifts (not shown) (from Binns, et al, 1974).

that acted as conduits for these magmas. A number of greenstone belts, such as the Murchison Range Belt in the Kaapvaal Craton, appear to be preserved along major taphrogenic faults suggesting that the greenstone belts preferentially developed on rifts that cross-cut the early gneissic sialic crust. In the well preserved Archean Cratons, the greenstone belts are fairly extensively developed (Fig. 13), suggesting that the volcanic activity in the Archean was evenly distributed, even though it was possibly sited and concentrated along major rifts. Re-clustering the continents as Gondwanaland in the Late Palaeozoic aligns the presently diverse Archean orogenic patterns of at least South Africa, India and Australia, suggesting that there might have been a primary tectonic control on their development (Engel, et al, 1974).

Although the present distribution of the Archean is largely a function of age and subsequent over-printing by later orogenies, the Archean orogenic terrains have large absolute widths compared to the later Mesozoic Orogenic Belts. The elongate arcuate patterns characteristic of the Late Mesozoic Orogenic Belts are uncommon in the Archean, suggesting that deformation in the Archean was related to more localized orogenesis, with smaller wavelengths and amplitudes. The style of the Archean tectonics indicates a high plasticity as well as a close relationship between folding, the diapiric ascent of granitoid plutons and the process of granitization and anatexis. The intensity of plastic deformation appears to be directly related to the extent of the development of granitic material (Salop and Scheinmann, 1969). The presence of separate highly folded relics of supercrustal rocks or layered intrusions that retain a ghost stratigraphy in Archean granulite terrains is consistant with plastic deformation that carried the rocks, deposited on or close at the surface, to depths of up to 40km. It is at these depths that the pressures of 10-13 kb, suggested by the stability of coexisting mineral assemblages, would exist (Sutton, 1977).

The end of the Archean was marked by a great addition of tonalite and granodiorite plutons to the early sialic crust in such a way that they constitute up to four fifths of the resulting continental crust. During this process, which occurred high enough to affect the overlying supercrustal rocks, the pre-existing sialic crust was largely destroyed or concealed so that only small remnants are preserved in the rock record today. Both the earlier volcanic rocks and a majority of the plutonic rocks were derived from the mantle and lower crustal depths as indicated by the low Sr^{87}/Sr^{86} initial ratios. It is possible that the late-tectonic potassic granites that intruded the volcanic and sedimentary rocks between 2800 and 2600 my originated as a result of the anatectic mobilization of the basement gneissic-granites, in response to the large amount of heat transferred due to wide-spread mantle diapirism. Thermally induced density gradients might have been capable of forming the large gneiss domes as the large-scale equivalents of the younger "mantled gneiss-domes" (Salop and Scheinmann, 1969; Talbot, 1971). The interaction between the separate major granitic-gneiss domes would have resulted in the development of complex interference fold patterns within the adjacent greenstone belts. The major Archean orogeny culminated in development of a sialic crust with a greater thickness and rigidity and the subsequent thermal decay at ±2500my re-set most Archean Rb/Sr and K/Ar radiometric clocks (Engel, et al, 1974).

The development of the Archean greenstone belts granitoid plutonism and subsequent plastic deformation is thought to be associated with the transfer of large amounts of mantle-derived heat by mantle advection. The Archean is thought to have been characterized by extensive mantle diapirism. The large amounts of available thermal energy enabled high-degree partial melts to develop during the rise of the mantle diapirs. These magmas were probably extruded along rifts, initiated in the sialic crust in response to the rise of the mantle diapirs, to form thick domical piles of ultramafic to mafic volcanics. The interaction of magma diapirs with the sialic crust resulted in the generation of tonalite and granodiorite magmas that rose slowly through the crust as large diapir plutons. Magmatic differentiation within some of the earlier plutons probably generated the calc-alkaline volcanics that tend to post-date the ultramafic and mafic volcanics. The continued interaction of the magma diapirs with the sialic crust and generation of granitoid plutons caused instability which initiated collapse and the plastic deformation of the greenstone belts and the formation of mega-scale and smale-scale interference patterns. In some areas supercrustal rocks were carried to great depths and subjected to granulite metamorphism. In some areas the transfer of heat resulted in the partial and complete anatectic re-mobilization of the basement gneisses and the generation of migmatites and late-stage potassic granites. In general, the Archean was characterized by an extensive period of large-scale mantle advection that has not been repeated since.

THE EARLY PROTEROZOIC

The Early Proterozoic marks the beginning of a major evolutionary stage of the earths history, characterized by platforms and geosynclines, that represent a transition from the per-mobile Archean cycle to the Mesozoic-Cainozoic Continental Drift Cycle. Platforms are large portions of continental crust characterized by tectonic stability over long periods, of time, of several hundred million years or more. Platforms tend to have a general tectonic homogeneity despite a complex inner structure that is characterized by separate zones formed at different times (Salop and Scheimann, 1969). Geosynclines are in contrast, tectonically unstable zones characterized by episodes of rapid differential movement.

Geosynclines can be subdivided on the basis of their tectonic, volcanic, sedimentary and plutonic associations into miogeosynclinal and eugeosynclinal zones.

Miogeosynclines are characterized by the predominance of shallow-marine sandstones, shales and carbonates, deposited in a slowly subsiding basin, that are subsequently affected by low-grade metamorphism and gentle deformation. Eugeosynclines on the other hand are characterized by thick sequences of tholeiitic volcanics and immature greywackes deposited in a rapidly subsiding trough and later subjected to intense deformation and high-grade metamorphism. Miogeosynclines and eugeosynclines are commonly separated by an extensive basement highs that remained active during the evolution of the geosyncline (Fig. 15). These basement highs were zones of diminished sedimentation that continued to influence the facies distribution within the miogeosyncline. These basement highs were later incorporated into geanticlinal barriers, or tectonic borderlands, during the subsequent collapse of the geosyncline and associated deformation (Kay, 1951). Taphrogenic rifts often acted as boundaries to the geosynclinal belts. The faults not only determined the configuration of the platforms and geosynclines but also controlled the location of the volcanics and sedimentary deposits, as well as numerous plutonic bodies. These rifts were also zones of high permeability in the crust which is indicated by their association with belts of higher-grade metamorphism, anatexis and the ascent of granitic plutons (Salop and Scheimann, 1969).

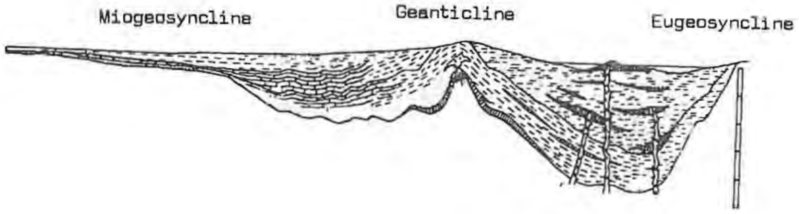


FIGURE 15: A typical section across a geosyncline showing the development of a geanticlinal zone separating the miogeosyncline, characterized by shallow marine sandstones, shales and carbonates, and the eugeosyncline, characterized by thick greywacke sequences and tholeiitic to calc-alkaline volcanics (from Kay, 1951).

The ratio of orthoquartzites and carbonates to volcanic wackes increased by several orders of magnitude from the Archean to Lower Proterozoic (Engel, et al, 1974), in response to a change from dominantly eugeosynclinal-type deposits in the Archean to thick sequences of Proterozoic platform and miogeosynclinal sediments on the stabilized Archean Cratons, as well as the associated eugeosynclinal sediments.

The oldest geosynclines originated on a fragmented Archean granitic basement that was subsequently refolded and granitized with the supercrustals during the Proterozoic orogenies (see Fig. 13). The presence of such roots to the mobile belts justifies the assumption hat the geosynclines found their expression as a result of local horizontal extension of the basement and associated differential subsidence. The platforms and geosynclines did not form round a stablized greenstone core, but formed as a result of the periodic splitting up of the Archean granite-gneiss basement (Salop and Scheimann, 1969). These ensialic belts formed in response to comparitively small relative movements of the stable cratons.

In North America the Superior, Slave and East Nain Archean Cratons which remained stable during the Proterozoic, are set in a network of high-grade metamorphic (mobile) belts that include the Churchill Province. The stable Archean Cratons are in part flanked by Proterozoic fold belts, which include the eugeosynclinal assemblages of the Lake Superior, Labrador and Coronation Geosynclines. Elsewhere however, the cratonic margins are defined by major tectonic lineaments that belong to a dominant north-east south-west set (Fig. 16) (Sutton and Watson, 1974). These linears are locally marked by lines of intrusions or narrow zones of intense deformation. The presence of marginal distorted earlier structures suggests that these zones are associated with major transcurrent displacements (Sutton and Watson, 1974). The linears, which plot on a small circle, are orientated at an angle to the trends of the Lake Superior, Labrador and Coronation Geosynclines. Horizontal extension associated with the development of the Lake Superior, Labrador and Coronation Geosynclines and subsequent deformation and compression probably initiated differential movements along these transcurrent lineaments. Paleomagnetic measurements of neighbouring Archean Cratons suggest that they followed similar apparent polarwander paths, indicating that great differential movements probably did not occur between the crustal blocks. The sialic crust therefore reacted to

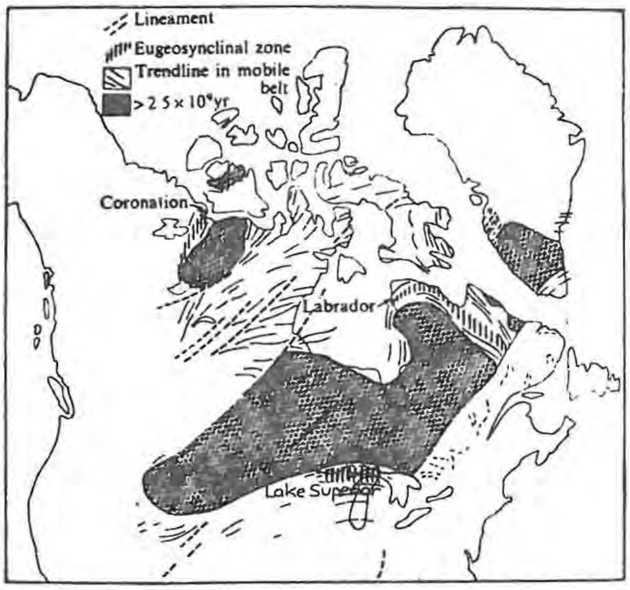


FIGURE 16: Some Early Proterozoic structures in North America and Greenland illustrating the development of eugeosynclines marginal to the stable Archean Cratons and the presence of major shear zones separating the craton from adjacent metamorphic belts. Parallel shear zones also occur within the metamorphic belts and within the craton (from Sutton and Watson, 1974).

movements in the mantle at the time of the climax of the Hudsonian orogeny by internal deformation, taken up partly in the mobile belts of the time and through movements along narrow belts of high strain which developed in the otherwise stable Archean Cratons (Sutton, 1977). The wide-spread Early Proterozoic, Hudsonian-age deformation of the crust differed from the Archean peak of tectono-thermal activity in that more of the crust escaped the most intense effects and may have differed from younger periods of tectonism and igneous activity through the development of numerous vertical belts of high strain within the more extensive orogenic belts that allowed the large cratonic platforms to retain their entity by being subjected to only mild deformation and metamorphism (Sutton, 1977).

The Lower Proterozoic Geosynclines are characterized by linear folds grouped together into elongated belts or large arcs that are convex towards re-entrant angles between platform blocks (Fig. 17). The large-scale highly deformed basin and dome structures characteristic of the Archean granite-greenstone terrains were no longer prominant in the Proterozoic. Locally, however, smaller-scale gneissic-domes developed within the more intensely deformed and metamorphosed zones of the eugeosynclines.

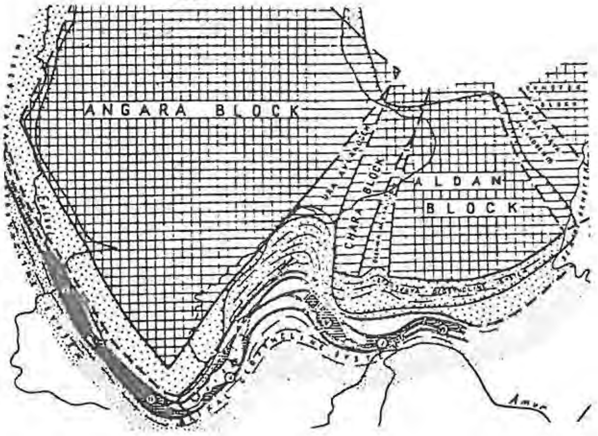


FIGURE 17: The geometry of Early Proterozoic geosynclines around the Archean Siberian Craton. Miogeosynclinal zones develop between the Platform and a boundary zone of basement highs, which separate the miogeosyncline from the eugeosyncline Major aulacogens develop at re-entrants into the cratons and grade into the miogeosynclines (from Salop and Scheinmann, 1969).

The 2150-1850my Lake Superior and Labrador Geosynclines occur in similar geological settings and underwent similar evolutionary stages. These geosynclines are developed on the boundary of the stable granite-greenstone terrain and adjacent basement gneisses. Extensive faulting and dyking initiated basin development in the eugeosyncline situated on the basement gneiss terrain. The volcanics in the eugeosyncline are mainly tholeiitic, with associated differentiated mafic sills spatialy related to the lavas in both regions. The sediments and volcanics in both were deformed and metamorphosed during the Hudsonian (Penokean) Orogenies that terminated the deposition of these Proterozoic rocks. Tectonic transport in both basins was towards the inner parts of the craton accompanied by overturned tight folds and numerous faults. Metamorphism is low-grade in the Miogeosynclines and higher-grade, with steeper thermal gradients, in the eugeosynclines. Both contain anatectic pegmatites and granites in the areas of high-grade metamorphism, while the Lake Superior Geosyncline also contains late to post-tectonic and anorogenic calc-alkaline plutons.

The Early Proterozoic sediments in the Lake Superior Geosyncline were deposited in ensialic basin centered on a major, probably rift-controlled boundary between a granite-greenstone terrain and basement-gneiss. Stable miogeosynclinal sedimentation, with early stable shelf quartzites, stramatolitic dolomites and major banded iron formations, extended across the whole platform that developed on the stable granite-greenstone terrain of the Superior Province. Differential subsidence in the area underlain by basement gneisses resulted in the rapid development of a thick eugeosynclinal sedimentary succession of greywackes, mafic and felsic volcanics and local thin banded iron formation units. The eugeosyncline is characterized by a number of marked unconformities and a much thicker sediment accumulation (Sims, 1976).

The relatively undeformed sediments on the platform dip gently to the south-east, while to the south of the rift-controlled boundary the cover rocks are tightly folded together with the underlying basement gneisses (Fig. 18). The eugeosynclinal zone contains infolded basement gneiss domes and in other places uplifted basement blocks, bounded on at least some margins by major faults. During deformation the basement gneisses behaved in a mobile fashion to produce "mantled gneiss-domes" with associated anatectic granites. The main difference between the gneiss-domes and structurally equivalent fault-bounded uplifted blocks of gneiss is probably related to the plasticity of the rocks during deformation. "Gneissic-domes" are the result of ductile deformation and are accompanied by refoliation, metamorphism and partial melting, while the antiformal fault-bounded blocks are less intensely deformed and are characterized by cataclastic deformation, minor recrystallization and local anatexis. In the southern part of the basin four nodes of high-grade, low pressure metamorphism are associated with uplifted blocks or domes of Archean basement gneiss (Fig. 19). One of these nodes contains a differentiated syn-orogenic gabbroic body within the silliminite isograd, indicating a direct relationship between mantle processes and metamorphism (Sims, 1976).

FIGURE 18: The variation in structural style across the Lake Superior Geosyncline from the relatively unmetamorphosed gently-dipping sediments of the platform to the highly folded eugeosynclinal sediments and reactivated basement domes. Note that the change in structural style corresponds to a postulated rift zone (from Sims, 1976).

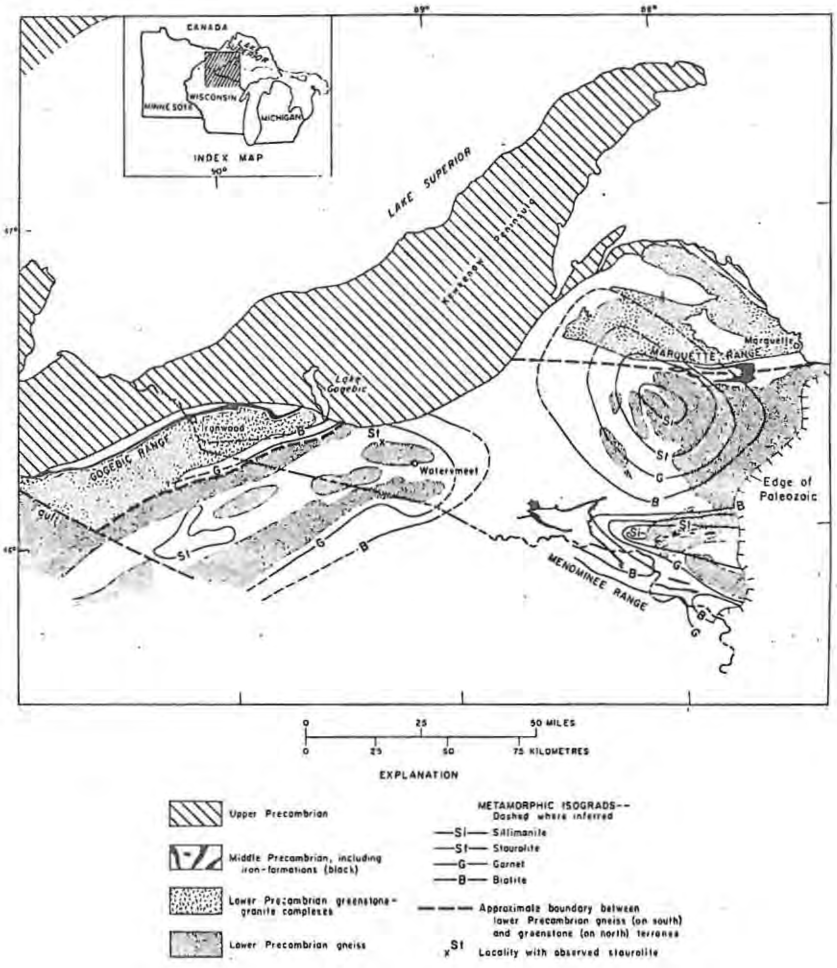


FIGURE 19: Zoned metamorphic patterns in the Lake Superior Geosyncline centred on reactivated basement domes (from Sims, 1976).

Aulacogens are very large, 100-200km wide, graben-like structures that preferentially develop at the apex of a major re-entrants of the geosynclines into the platforms. The aulacogens are characterized by a distinct radial pattern away from the geosyncline so that they gradually die out in the middle of the platform. Aulacogens are usually long-lived features that subside during the entire history of the related geosyncline. Most aulacogens begin as narrow rift-bounded grabens, that are susceptible to periodic reactivation, and later become much wider downwarps (Hoffman, Dewey and Burke, 1974). The tectonic activity during sedimentation increases towards the edge of the platform so that subsidence is greater and the sediments thicker and more diversified in composition. The sediments eventually acquire the features of the miogeosyncline where the aulacogen merges with the geosyncline. In response to intense tectonic activity in the eugeosyncline the aulacogen generally becomes of zone of gentle to moderate folding, which eventually becomes segmented by reactivation of the original bounding rifts. The intensity of deformation in the aulacogen gradually dies out away from the geosyncline. These features indicate that the bounding rifts of the aulacogens are major crustal features and suggest that the activity at depth under the platforms cannot be regarded to be independent of the activity under the geosynclines (Salop and Scheinmann, 1969).

Two major aulacogens are developed marginal to the Coronation Geosyncline. The Athapuscow and Bathurst Aulacogens are co-extensive with the north-east trending McDonald Fault and the south-east trending Bathurst Fault system respectively (Fig. 20). The supracrustal fill in the aulacogens is much thicker and more deformed than the adjacent nearly flat-lying platform cover (Fig. 21). The folded and complexly faulted sediments of the Athapuscow Aulacogen thicken from 2200m to greater than 7000m in the direction of the geosyncline, in contrast to the adjacent fairly constant 1400m thick platform sediments. The aulacogen remained a periodically reactivated narrow rift-bounded graben during the deposition of a westward facing continental shelf sequence in the miogeosyncline. The initial rift-bounded graben had elevated margins from which the early phases of deposition are absent. The aulacogen

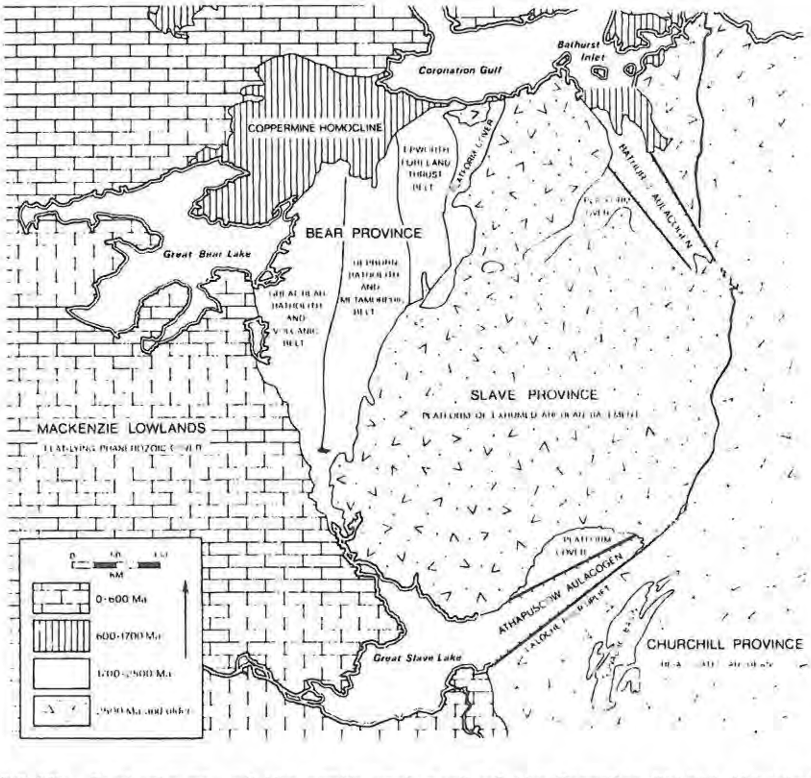


FIGURE 20: Tectonic map of the north-west part of the Canadian Shield illustrating the development of the Early Proterozoic Athapuscow and Bathurst Aulacogens off the Coronation Geosyncline along major rifts, one of which separates the Slave and Churchill Provinces (from Hoffman, et al, 1974).

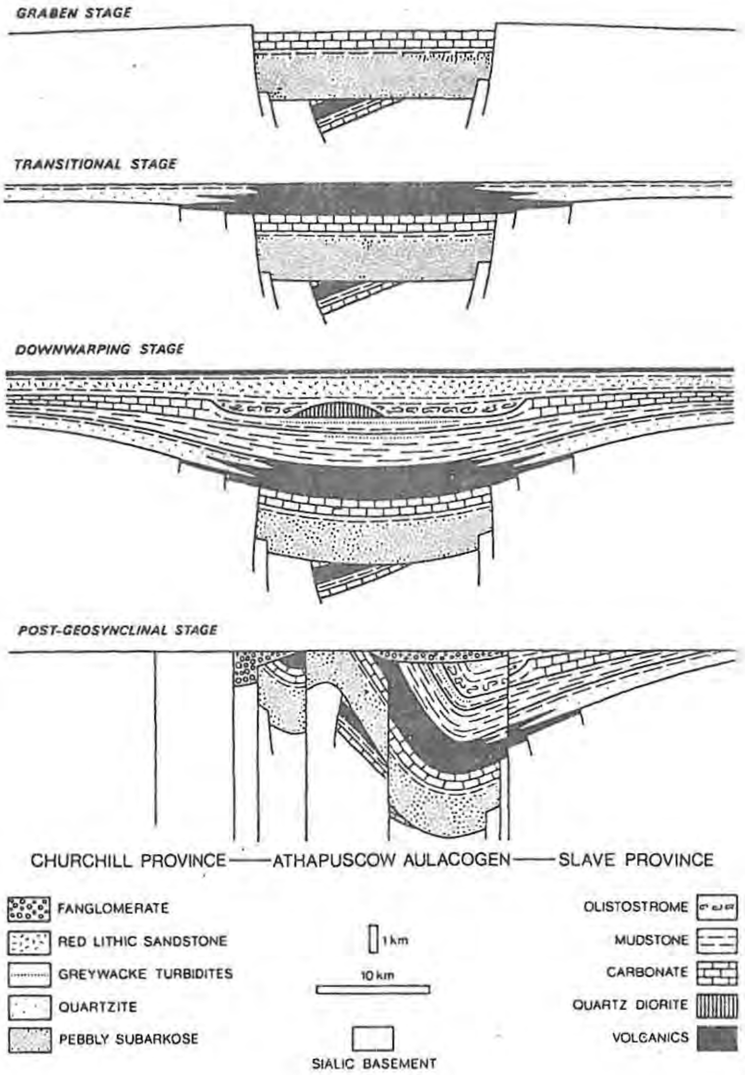


FIGURE 21: Schematic transverse cross-sections showing the evolution of the Early Proterozoic Athapuscow Aulacogen (from Hoffman, et al, 1974).

then became a zone of broad downwarp with the deposition of shallow-marine sediments and was ultimately subjected to mild transverse compression coeval with the development of a westerly derived clastic wedge in the eugeosyncline and miogeosyncline. This new sediment source was due to uplift of the tectonic borderland formed by the collapse of the Coronation Geosyncline and associated compressional deformation and vertical uplift. The aulacogen finally became an active fault zone with transcurrent movement in addition to vertical movement. Alluvial fanglomerates, derived mainly from the uplifted Coronation Geosyncline, were then deposited in the Aulacogen in response to the vertical uplift (Hoffman, et al, 1974).

The sediments within the Athapuscow Aulacogen show a parallel facies development to that of the adjacent miogeosyncline. However, the aulacogen responds more to tectonic variations in the eugeosyncline. The rapid development of the initial yoked-basin parallels the development of a deep eugeosynclinal trough and then finally, in response to orogenic inversion of the Coronation Geosynclines, the aulacogen is subjected to reactivation along the controlling rifts with the subsequent deposition of coarse-grained clastic sediments in a successor-type yoked-basin.

The Early Proterozoic basin development in the North American Craton illustrates the features associated with the development of geosynclines and aulacogens and their control on sedimentation, volcanism and plutonism. It appears that these geosynclines preferentially developed at the boundary between the stable Archean granite-greenstone belts of the Superior Province and adjacent Archean basement gneisses. The reactivation of bounding rifts by mantle diapirism would have resulted in horizontal extension and the rapid subsidence of a eugeosynclinal trough with associated tholeiitic volcanism and later deformation, metamorphism, reactivation of the basement gneisses and plutonic activity.

The roughly zonal development of the Early Proterozoic Geosynclines round a stable craton has led to the development of a concept of continental accretion. However, in the Lake Superior Region, instead of younger rocks being added in successive crudely zonal patterns, as suggested by the ages of the geological provinces (Fig. 22), the data suggests that the craton had probably attained its present dimensions by the close of the Archean stage at ±2500my. The zones that yield "Proterozoic" ages represent both re-mobilized Archean basement and younger supercrustal and plutonic rocks (Sims, 1976).

<u>FIGURE 22</u>: Map of SE Canada showing the development of the Early Proterozoic Geosynclines (2200-1800my) on the periphery of the stable Archean Superior Province (2500my). The marginal Grenville Belt (1000my) and Phanerozoic cover complete the apparent concentric-age pattern. However, the North American Craton probably attained its present dimensions at the end of the Archean (from Windley, 1977).

THE MID PROTEROZOIC

Further evolution of the earths crust during the later Proterozoic consisted in the gradual growth of platforms at the expense of the geosynclinal belts. This general tendency was however, periodically interrupted by collapse and subsidence of separate parts of the stabilized blocks. During the Mid Proterozoic many continents were intruded by peculiar platform-type differentiated plutonic complexes, consisting of variable proportions of norite, gabbro, granophyric rapikivi-granites, alkaline rocks and anorthosites. This post-orogenic plutonism is separated by a considerable period of tectonic quiet from the syn-orogenic plutonism in the Early Proterozoic Hudsonian (±1850my) metamorphic belts (Salop and Scheinmann, 1969). A major belt of massive anorthosite and rapakivi granite plutons stretches from the Urals in the east, to the west coast of North America (Fig. 23). These plutons are developed within areas that were involved in the Hudsonian-age Orogeny and tend to avoid the stable Archean Cratons.

The anorthosite complexes are closely related in space and time to a group of norites, monzonites, quartz-syenites and rapakivi-granites that show a broad-scale younging from the east to the west. The same belt also contains isolated fault-bounded basins filled by thick sequences of continental sediments and intercalated volcanics that have a close association with the plutonic activity. The sediments and associated volcanics range considerably in age, from the 1800-1600my Jotian Group on the Baltic Craton to the 1400-1000my Keweenawan Group of central

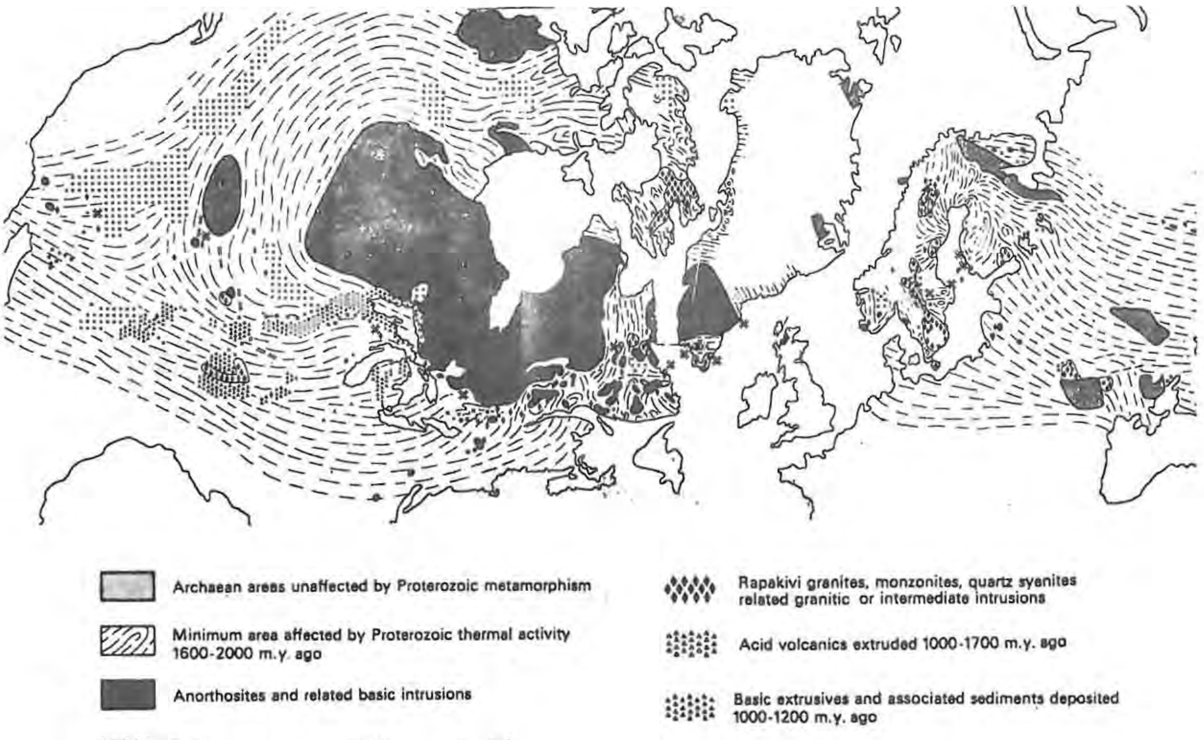


FIGURE 23: The distribution of Mid-Proterozoic anorthosites, rapakivi granites, felsic and mafic volcanics and sedimentary basins which developed from the west coast of America to the Urals (from Bridgewater and Windley, 1973).

North America. In general, the anorthosites and rapakivi granites formed prior to the sedimentation and volcanism, although there is a considerable overlap in some areas (Bridgewater and Windley, 1974). In places the upper parts of the rapakivi granite plutons intrude undeformed intermediate to felsic volcanics and associated continental sediments. The major rifts that controlled the sedimentation were active for a considerable time during and after deposition and also acted as zones of increased pemeability for magmatism. In both Greenland and Finland the fault zones remained the dominant control for magmatism for up to 500my after the deposition of the initial continental sedimentary sequences. The magmatic activity ranges from felsic volcanics, which are the surface equivalents of the rapakivi granites, to basic and alkaline plutons emplaced up to 500my after the main peak of anorthosite formation. Tholeiitic and alkali basaltic volcanics commonly occur in the same area, although the alkaline magmatism appears to be more restricted to distinct fault-controlled belts and to have persisted for a longer period of time than tholeiitic magmatism. Nepheline syenite and carbonatite complexes are developed along a number of major lineaments within the Archean

Cratons, adjacent to the main areas of Mid Proterozoic magmatism (Bridgewater and Windley, 1973).

In Greenland the magmatism is characterized by elongate mushroom-shaped intrusions of massive anorthosite that can reach up to 5000km^2 in area. The undersides of these intrusions are typically funnel-shaped, in that a vertical stem occurs adjacent to inward-dipping downfolded host rocks (Fig. 24). These stems, which vary from 2-10km in width and 40-80km in length, are generally localized by major rifts. The upper mushroom-shaped parts of the plutons appear to have been emplaced along suitable horizontal weaknesses in the sialic crust. The norite-monzonite-rapakivi granite plutons are generally smaller than the anorthosite plutons, although they can reach upto 100km by 40km in area. High-temperature low-pressure metamorphism and steep thermal gradients are associated with the intrusive plutons. The mineral assemblages in the metamorphic aureoles indicate that the maximum depth of crystallization was probably 6 km (Bridgewater, Sutton and Watterson, 1974).

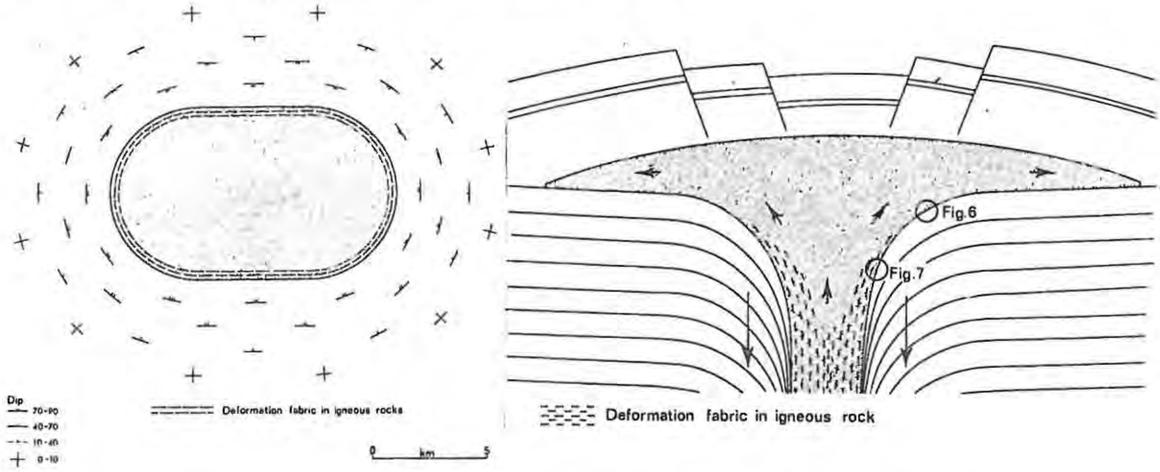


FIGURE 24: Idealized plan (A) and vertical section (B) of a rapakivi granite pluton showing the attitude of the country rocks and the development of grabens above the pluton (from Bridgewater, Sutton and Watterson, 1974).

The massive anorthosites are thought to have formed at depth, probably as a result of large-scale magmatic differentiation at the base of the sialic crust (Fig. 25). This magmatic activity probably generated the high heat flow associated with the Hudsonian-age metamorphism and was confined by crustal compression during orogenic deformation. The anorthosites are thought to have risen through the ductile sialic crust in response to a density inversion. This movement was initially confined to faults and then the crystal mushes extended outwards to form mushroom-shaped plutons at particular crustal levels. Lateral spreading

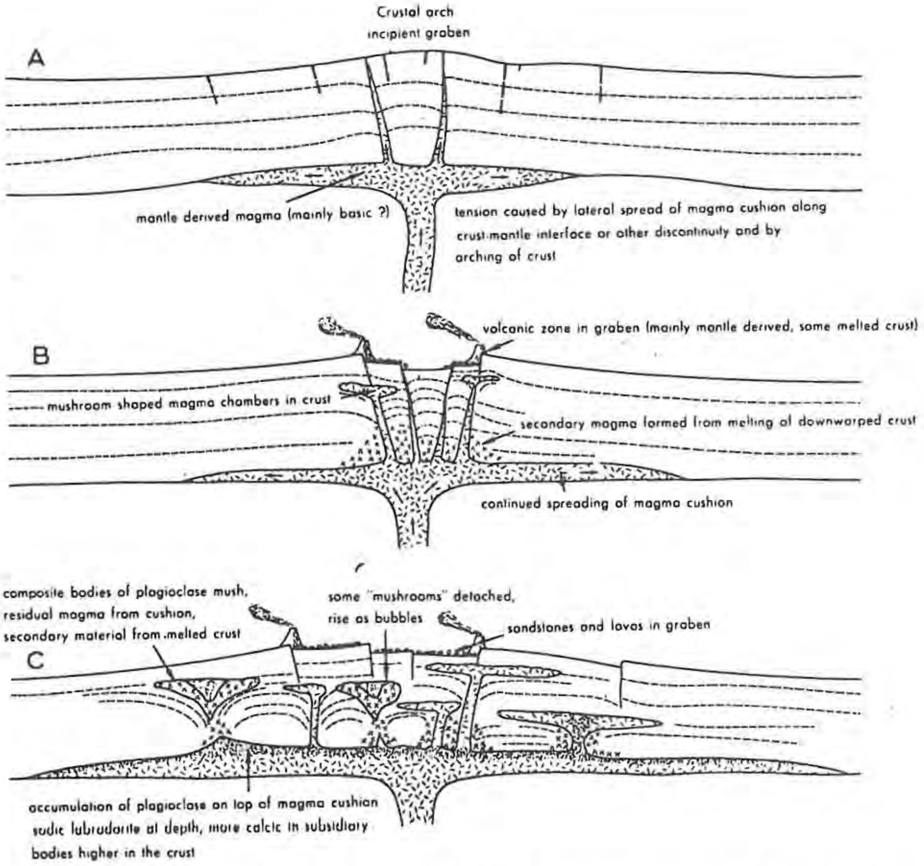


FIGURE 25: Model relating the development of anorthosites, rapakivi granites, felsic and mafic volcanics and graben structures in the sialic crust. (A) Crustal doming associated with a mantle diapir. (B) Rifting and graben formation and volcanic activity associated with the spread of the mantle diapir. Interaction of mafic magmas and the sialic crust generates magmas that form differentiated norite-monzonite-rapakivi granite plutons at higher crustal levels. (C) Fractional crystallization of basaltic partial melt at depth forms plagioclase cumulates that rise diapirically to form massive anorthosites. Some anatectic partial melting of downwarped continental crust (after Bridgewater, Sutton and Watterson, 1974).

can only occur in response to the generation of space, either by updoming of the overlying rocks or by subsidence of the underlying rocks, or a combination of the two. Rifting and the development of grabens would be associated with doming of the overlying sialic crust and possible associated viscous drag in response to the lateral spreading of the pluton. The interaction of mantle material with the lower crust probably generated the magmas that eventually spread out at higher levels in the crust to form mushroom-shaped norite-monzonite-rapakivi granite complexes (Bridgewater, Sutton and Watterson, 1974). It is possible that the Mid Proterozoic crust was more ductile following the major Hudsonian 'event' and as a result there was less viscosity difference between the plutons and lower crust. This, therefore, enabled mantle and lower crustal derived magmas to rise slowly through the crust as plutonic bodies. This initiated graben formation rather than cauldera collapse and allowed the magmas to crystallize to form plutonic bodies with minor associated surface volcanism. The isolated rift-bounded troughs that developed vertically above the plutonic complexes were the site of subaerial volcanism and rapid clastic sedimentation in response to periodic vertical uplift. Locally, shales and minor pillow lavas were formed in restricted playa lakes.

The plutonic activity and deposition of surface sediments and volcanics are closely related in time and space and in addition the fundamental conditions that controlled their formation are remarkably similar. This major crustal zone was characterized by tectonic instability, abnormally high thermal gradients and considerable magmatic activity, for a period of at least 800-1000my. The relatively linear distribution of the anorthosite and granite plutons, volcanic activity and the development of grabens, and possibly the subsequent metamorphism during the Grenville Orogeny (±1000my) appear to all have been controlled by the same major feature in the crust and upper mantle. It is also significant that a higher concentration of anorthosite plutons occur in the vicinity of the area most affected by the Grenville Orogeny (Fig. 23) Bridgewater and Windley, 1973).

While most of the Mid Proterozoic were characterized by extensive cratonic instability and the development of interior rift-bounded basins, a series of ensialic fault-bounded basins developed on the western margin of the North American Craton (Fig. 26). These marginal basins were filled by the sediments of the Belt and Purcell Supergroups (1450-850my) in a series of overlapping and coalescing sedimentary wedges that prograded out from the adjacent platform. The sedimentary sequence includes units deposited on deep basinal submarine fans, prograding deltas and in shallow-marine and tidal flat environments, which are in contrast to the coarse-grained alluvial fan deposits that characterize the intra-cratonic yoked-basins. A major rift-controlled aulacogen, the Kimberley Aulacogen, extends for up to 450km away from one of these marginal basins into the platform (Fig. 26) (Kanasewich, 1968). Seismic studies have shown that the Moho Discontinuity changes elevation abruptly beneath this aulacogen indicating that it is a major structural feature associated with disturbances in the mantle. Near its western limit the aulacogen was filled by 11km of sediments. This corresponds closely to the 11-15km thickness of the Purcell and Belt Supergroup sediments in the adjacent trough and indicates a similar relationship between aulacogen and trough as that between miogeosyncline and aulacogen in the Early Proterozoic.

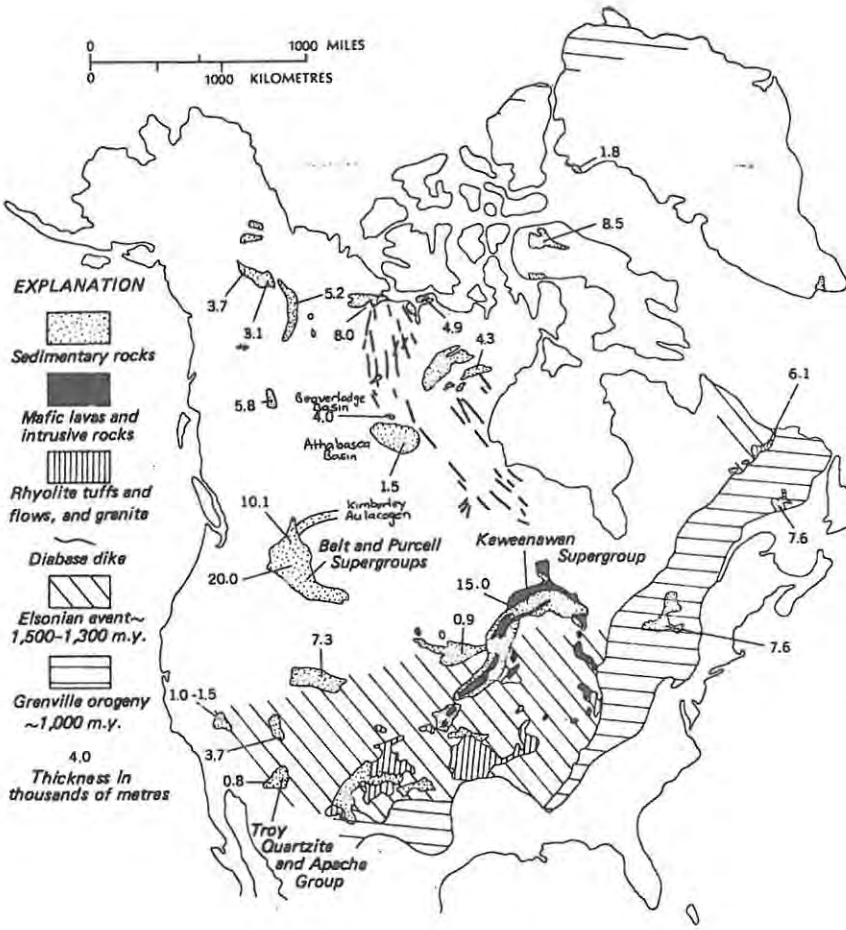


FIGURE 26: The distribution of Mid to Late Proterozoic sedimentary and volcano-sedimentary basins on the North American Craton. The Elsonian 'Event' and Grenville Orogeny include igneous activity and metamorphic overprinting of older crustal rocks (from Stewart, 1976).

The Keweenawan Rift is a major intra-cratonic rift, developed in the centre of the North American Craton, that is filled by a 15000m thick sequence of tholeiitic volcanics and lesser continental clastic sediments (Fig. 26). The continuation of the Keweenawan Rift is marked by a 1300Km linear zone of gravity and magnetic anomalies beneath Palaeozoic cover that suggests that rift varies between 40-85Km wide along its whole length (Chase and Gilmer, 1973).

The supercrustal rocks deposited between 1700my and 850my are scattered throughout the North American Craton. Most of these sediments and volcanics were deposited in yoked-basins, while some were deposited on the platform and in shallow troughs on the cratonic margins. The presence of rift-bounded troughs and the abundance of mafic intrusive and extrusive igneous rocks suggests that wide-spread extensional events occured during the interval between 1700-850my. Crustal extension appears to have taken place sporadically across the entire craton, initiating rifts and leading to the local emplacement of mafic intrusive and extrusive magmas, that is in contrast to the younger Mesozoic where extension is confined to the margins of the craton (Steward, 1976). Mantle diapiric activity seems to have been diffuse and is not concentrated as it has been beneath the mid-oceanic ridges since the Mesozoic. This diffuse activity led to local plutonism in a relatively ductile crust, that existed after the extensive Hudsonian 'event', and associated rifting and development of confined yoked-basins. The episodic intra-cratonic rifting was probably associated with the development of a major geosyncline to the south that was eventually closed during the ±1000my Grenville Orogeny. It would appear that in the North American Craton there is a general migration of ages of active sedimentation and orogeny to the south, as the older Athabascan and associated basins in the north-western Canadian Platform were active prior to and during the Elsonian 'Event' (Fig. 25), while that later Keweenawan-age rifts developed on areas that had been affected by the Elsonian 'Event' and remained active up to the end of the Grenville Orogeny. The Keweenawan Rift was perhaps a concerted effort of horizontal extension and incipient crustal separation that was soon aborted. This episodic intra-cratonic tectonic activity eventually subsided and allowed the extensive deposition of stable shelf sediments in the encircling miogeosynclines. This extended period of intra-cratonic basin development is therefore equivalent to the development of proto-basins during the initiation of geosynclines and is probably a reflection of the early stability of the North American Craton.

THE LATE PROTEROZOIC - PALAEOZOIC

Late Proterozoic and Palaeozoic rocks are best preserved as long sinuous belts in most continents. This tectono-sedimentary period has been termed by some the "Pan African Event". Periods of geological activity within a specified time range and the continuity of tectonism, deformation, metamorphism and intrusive igneous rocks, without a break from one region to another, gives this event an aspect of unity in space and time (Hurley, 1973). When defined broadly enough, by including the Caledonian, Acadian, Avolonian, Damaran, Caririan and Hercynian Cycles, the Pan African 'Event' is preserved on all the continents and extends from the Late Proterozoic, after the Grenville Orogeny, through to the end of the Palaeozoic. Most of the orogenic activity is, however, concentrated in the 550-300my period (Hurley, 1972). The Grenville-age Orogenies at ±1000my were followed by a relatively amagmatic period of 400-500my that is characterized by early sedimentation in rift-bounded proto-basins and later deposition in large geosynclinal belts. These geosynclinal belts were eventually incorporated into the sinuous fold belts during the subsequent Pan African Orogeny. Individual belts appear to have developed at different rates, so there is as a result, a considerable variation in the ages of orogeny. It would appear that in a specific region the "Pan African Event" is recorded by a single major cycle of sedimentation, volcanism and subsequent orogeny, although in Europe the Hercynian Cycle (±280my) followed on after the Caledonian Cycle (±389my).

The Pan African domains, which cover nearly two thirds of Africa, define a reticulate pattern of acuate fold belts that surrounds sub-circular cratons. Within the belts themselves there are smaller areas that yield ancient ages, or by field evidence, can be shown to be an old basement virtually unaffected by the Pan African Orogeny. In many places it is also possible to prove continuity of older Archean and Proterozoic domains across the Late Proterozoic-Palaeozoic Pan African Belts. In Africa, sediments characteristic of eugeosynclines are inconspicuous in many parts of the Pan African Belts, but there are extensively developed in north-eastern Africa and in South West Africa (Shackleton, 1976). In many places it is possible to prove the stratigraphic continuity from the platform sediments into their folded and metamorphised equivalents in the orogenic belts. Basic intrusive complexes and associated serpentinites are persistently found within the Pan African Belts, but no complete ophiolite sequence has been recognized in Africa. The metamorphism is mostly characterized by Barrovian-type intermediate pressure facies, while blueschist facies metamorphism is generally absent. The distribution of the plutonic rocks within the belts is uneven and are they best developed at the intersection of two major trends in close association with granulite-grade metamorphic rocks (Shackleton, 1976). This is well illustrated by the intersection of the Khomas Trough (an aulacogen) with the main eugeosyncline of the Damara Belt. This intersection node is characterized by an intense basin and dome structural style of deformation, high-grade metamorphism and local anatexis, as well as the intrusion of large granitic plutons along major fault zones or rifts. The Damara Cycle in South West Africa was characterized by rather rapid development following the 1000my tectono-thermal event in the Namaqua Metamorphic

Belt. The early deposition of thick continental clastic wedges was confined to isolated proto-basins. Rapid subsidence along major rifts resulted in the deposition of mainly basinal volcaniclastic and epiclastic sediments in an eugeosynclinal trough and in the adjacent aulacogen, contemporaneous with the deposition of miogeosynclinal shallow-marine carbonates and clastic sediments on the adjacent shelves (Fig. 27). Calc-alkaline volcanism was confined to the major boundary rifts, while minor late-stage bimodal basalt-rhyolite volcanism is confined to the Khomas Aulacogen. The geosynclinal development was culminated by orogenic inversion at the end of the Precambrian, together with the intrusion of granites. The northern miogeosynclinal shelf of the Damara Geosyncline is separated from the adjacent eugeosynclinal deposits by an arcuate group of basement domes (Fig. 27). These basement domes remained active right through deposition as they influence both the thickness of individual units and the facies distribution. These basement highs separate thick accumulations of miogeosynclinal from eugeosynclinal sediments on either side. These domes were the preferential sites of deposition of thick reef-facies carbonates, indicating that they remained positive features during the development of the geosyncline. The margins with the eugeosynclinal troughs are marked by prominent fault zones that remained zones of volcanic activity right through basin development.

On the Russian Platform, Late Proterozoic sediments are mainly confined to aulacogens and isolated yoked-basins. It was only during the Early Palaeozoic that a major miogeosynclinal sedimentary sequence extended across the earlier deposits confined to the proto-basins. During the Early Palaeozoic the first eugeosynclinal fore-deeps began to appear as a result of the growth and displacement of the miogeosynclinal wedges on the margins of the craton (Salop and Scheinmann, 1969).

In the Late Proterozoic (±850my) the tectonic pattern of the North American Craton changed from locally deep epicratonic proto-basins to a pattern of encircling marginal miogeosynclines (Fig. 28) (Steward, 1972). On the western margin this change is marked by the transition from the deposition of Belt and Purcell Supergroups in isolated proto-basins to the extensive deposition of the Windermere Group. The sedimentary sequence of the Windermere Group, which is remarkably similar along strike, grades rapidly from thin sandstone units on the platform to a 5000-8000m thick

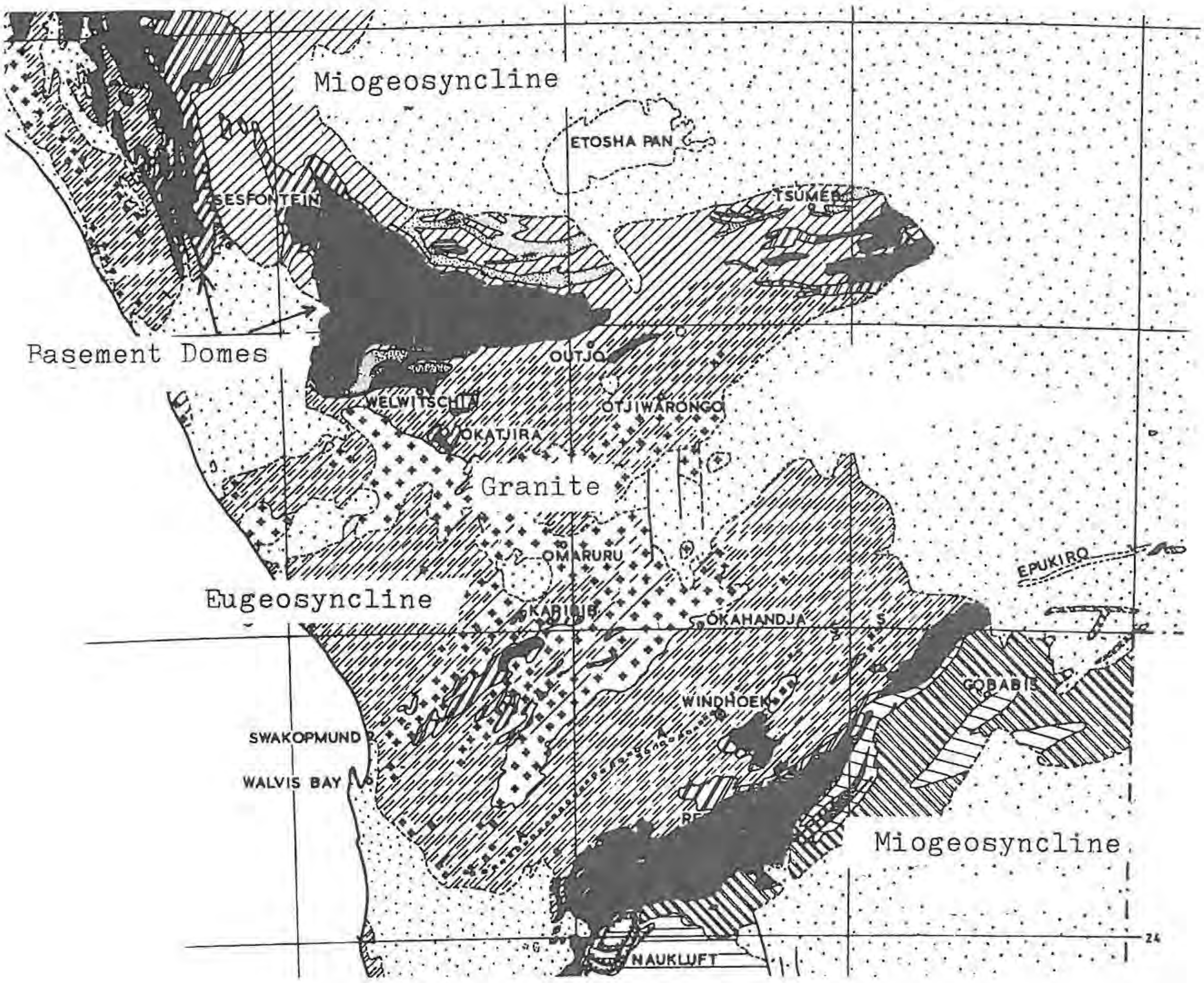


FIGURE 27: Map of the Damara Geosyncline illustrating the separation of the miogeosyncline from the eugeosyncline by a series of basement domes (from Martin, 1965).

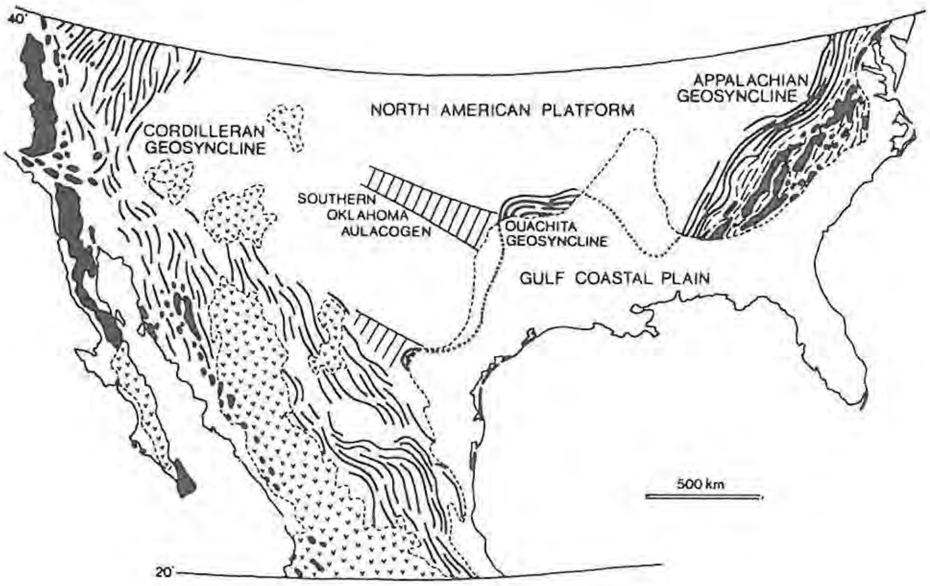


FIGURE 28: Map of part of North America showing the development of encircling geosynclines round the margin of the North American Platform and the development of aulacogens at major re-entrants (from Hoffman, et al, 1974).

miogeosynclinal sequence with lower eugeosynclinal deposits developed on a sialic basement to the west (Fig. 29). Volcanic rocks, mainly tholeiitic basalts are wide-spread in the lower part of the sequence and interfinger with the deep water sediments deposited in the eugeosyncline. The linear belt of westward thickening miogeosynclinal sediments deposited subsequent to the early volcanic activity indicates that the later deposition occured along a stable continental margin. The overlying Palaeozoic strata have an identical depositional pattern to the Late Proterozoic sediments. The Late Proterozoic sediments are therefore considered to be the initial deposits of the Cordilleran and Appalachian Geosynclines (Fig. 30) (Steward, 1976). Progressive progradation of the miogeosynclinal wedge away from the craton led to the development of the thick sedimentary sequences of the Cordilleran and Appalachian Geosynclines.

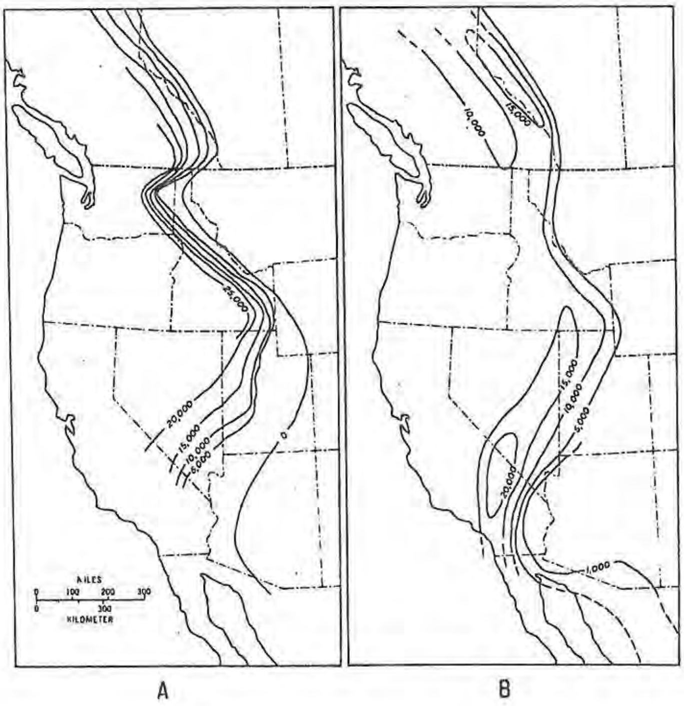


FIGURE 29: Isopac maps of units within the Cordilleran Geosyncline on the west coast of North America. (A) Initial Late Proterozoic Windermere Group; and (B) Cambrian to Silurian deposits. The geometry of the Late Proterozoic deposits is in marked contrast to the Mid-Proterozoic proto-basins (Fig. 26) (from Stewart, 1976).

The Southern Oklahoma Aulacogen extends off the Ouchita Geosyncline, the southern continuation of the Appalachian Geosyncline. The lower part of the aulacogen is filled by Late Proterozoic coarse-grained continental clastics with interbedded rhyolites, basalts and associated gabbroic

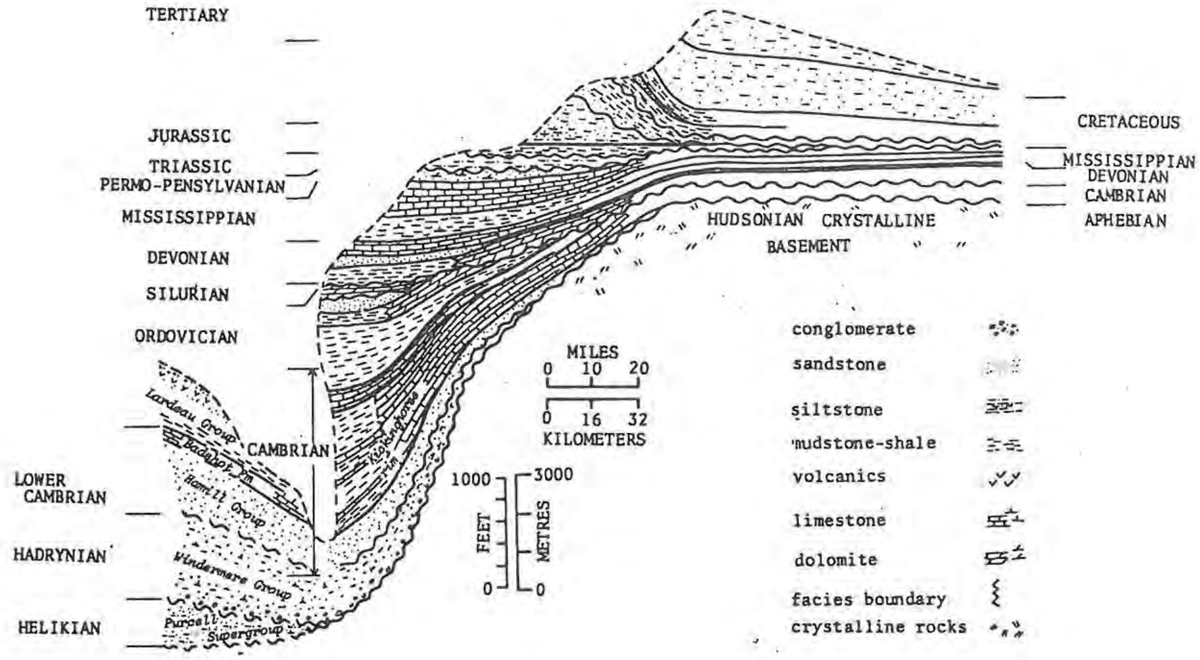


FIGURE 30: Schematic stratigraphic cross-section through the Cordilleran Geosyncline that first developed in the Late Proterozoic above Mid-Proterozoic sediments deposited in isolated proto-basins (from Thompson and Panteleyev, 1976).

sills. The aulacogen remained a zone of volcanic and granitic plutonic activity until the Mid Cambrian. The early sediments and volcanics deposited in the proto-basins are conformably overlain by a thick sequence of lower Palaeozoic carbonates and shales deposited in an extensive platform basin (Fig. 31). During this stage the aulacogen continued to influence thickness and facies distributions in the overlying miogeosynclinal sediments. The early basinal faults were reactivated during the Appalachian Orogeny which led to gentle folding and block faulting within the aulacogen and the subsequent deposition of coarse-grained continental conglomerates (Hoffman, Dewey and Burke, 1974).

The presence within the Appalachian Geosyncline of definite ophiolite complexes indicates that extreme crustal extension, and the associated development of simatic crust occured in Late Cambrian to the Mid Ordovician (±500-460my) at the end stages of the development of the Geosyncline. These ophiolite complexes, which reach up to 10km thick, were emplaced along sub-horizontal thrusts from the east during subsequent orogeny in the Ordovician (Fig. 32) (Windley, 1977). Andesitic volcanics occur interbedded with Cambrian eugeosynclinal sediments in the central part of the Appalachian-Caledonian Geosyncline. The andesitic volcanic piles show a close spatial relationship with the ophiolite

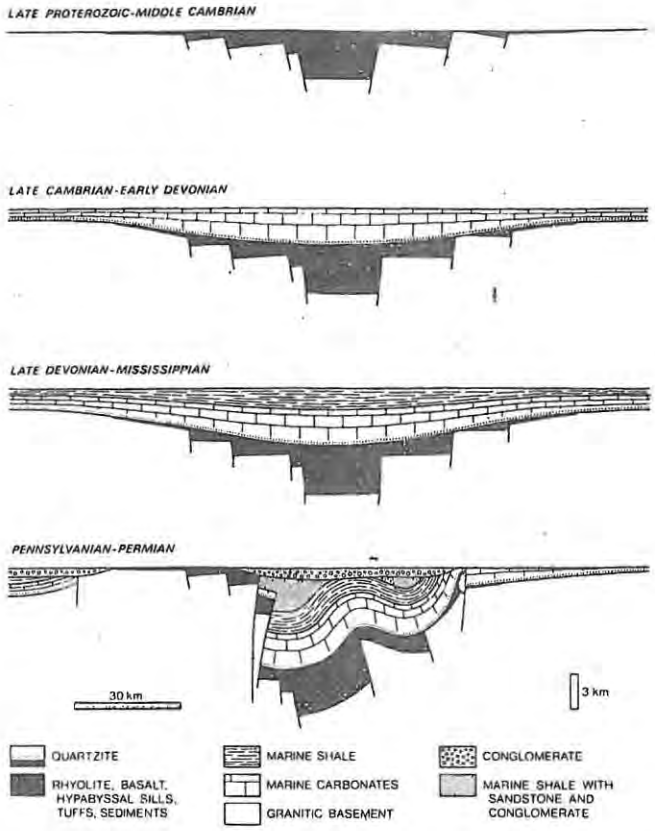


FIGURE 31: Schematic cross-sections showing the evolution of the Southern Okalahoma Aulacogen (from Hoffman, et al, 1974).

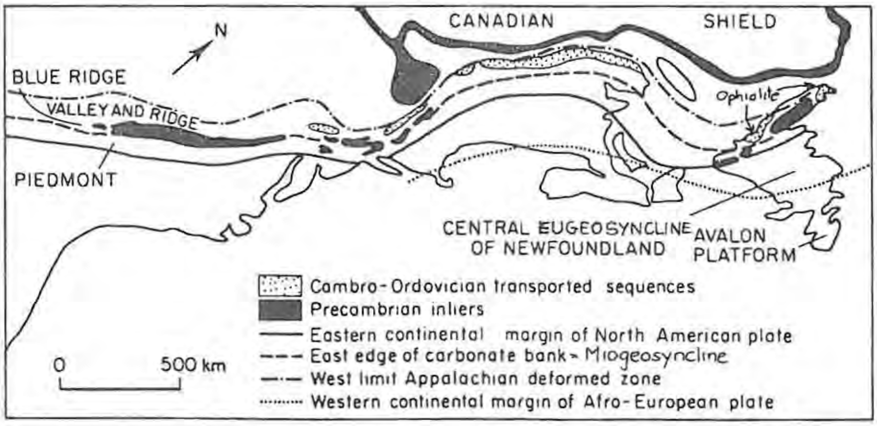


FIGURE 32: The Appalachian Geosyncline illustrating the development of basement highs at the interface between the miogeosyncline and eugeosyncline and the presence of ophiolite complexes in transported thrust sheets (from Windley, 1977).

complexes in the New Foundland area, possibly suggesting that intense tholeiitic volcanism and plate separation occured after the development of thick submarine andesitic volcanic piles associated with the early eugeosynclinal sediments.

The presence of different faunal provinces on the different sides of the Appalachian and Caledonian Geosynclines during the Cambrian to Mid-Ordovician (Windley, 1977) suggests that the Proto-Atlantic Ocean, separating the North American and Afro-European Cratons, was bisected by an elevated mid-ocean ridge.

The Appalachian Geosyncline is also characterized by a linear group of basement highs that separate the miogeosynclinal and eugeosynclinal basins in a similar pattern to that developed in the Damara Geosyncline (Fig. 32). These basement highs were reactivated into a tectonically active geanticline during the Appalachian Orogeny and provided the sediment source for the Late Ordovician molasse-type sediments deposited above the miogeosyncline (Fig. 33). During the orogenic deformation in the eugeosyncline, major block faulting and the fragmentation occured in the miogeosyncline.

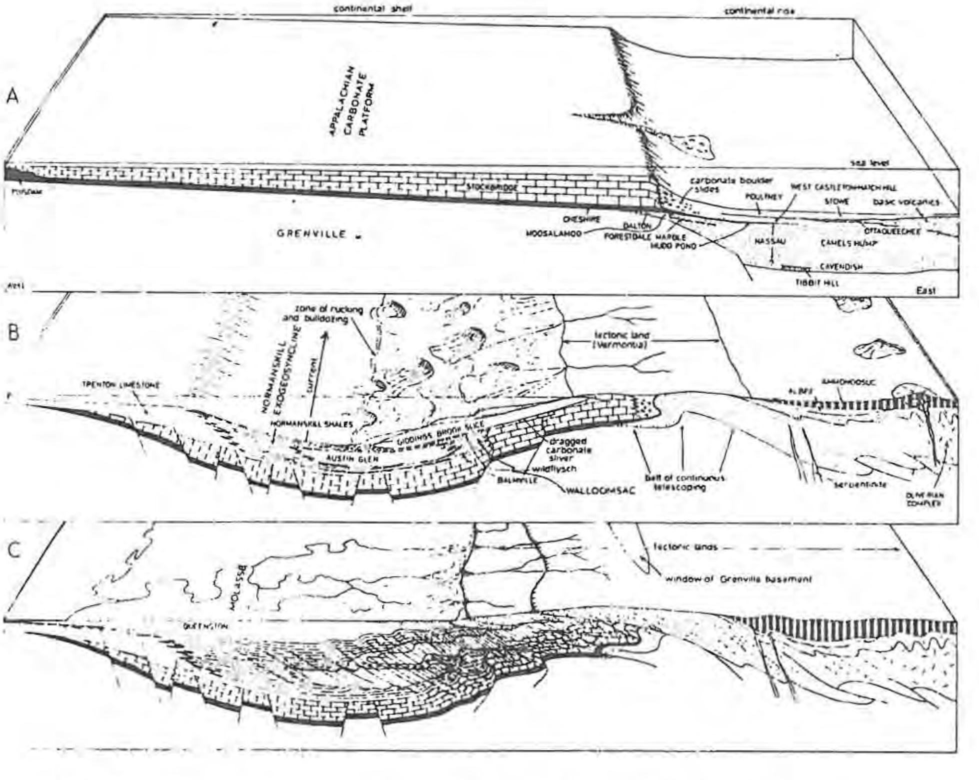


FIGURE 33: Schematic block diagrams illustrating the sedimentary and tectonic evolution of the continental margin of North America during the collapse of the Appalachian Geosyncline (from Bird and Dewey, 1970).

During the Late Proterozoic large internal uplifts orginated in many geosynclinal belts,dissecting them into zones of different tectonic regimes and increasing the zonality of the different facies. Intense orogenic processes in the Palaeozoic brought many geosynclinal belts into a state of inversion. Uplift of these zones associated with orogeny produced vast amounts of detrital material that was deposited as molasse-type sediments on the earlier miogeosynclinal deposits. Late Proterozoic - Early Palaeozoic metamorphism was of a linear nature, while granite intrusion occured locally in narrow zones along major faults or at their intersections. This is in contrast to the intense granite plutonism in geosynclines during the Early Proterozoic (Salop and Sheinmann, 1969). The presence of Late Palaeozoic ophiolites and blueschists in many of the Palaeozoic orogenic belts suggests that the large-scale continental rifting and continental drift, characteristic of the Mesozoic, had started (Engel, et al, 1974). However, large-scale drift of most of the continental segments seems precluded by the continued alignment of the older tectono-sedimentary domains across the Palaeozoic Belts. Some of the older Late Proterozoic-Palaeozoic geosynclines are essentially similar to the Early and Mid Proterozoic geosynclines while the later Palaeozoic Cycles show features of both geosynclines and the later Mesozoic plate tectonic cycle. Therefore the Late Proterozoic-Palaeozoic marks a transitional period in the evolution of the earth. Mantle processes had reached a stage when the generation of simatic crust and continental separation marked the end stages of the development of major geosynclines. However, these oceanic basins were unable to develop to any great extent due to orogenic inversion with associated deformation and metamorphism, including Blueschist facies metamorphism. "Blueschist" is, however, a confusing term as it represents a wide range of metamorphic mineral assemblages. The different assemblages of Blueschist facies metamorphism show a marked variation through time; epidote-bearing glaucophane schists are sporadically developed from approximately 600my, while jadeitic pyroxene-quartz assemblages show a marked increase in incidence at about 160my (Fig. 34) (Ernst, 1972). The appearance of blueschists in the Early Palaeozoic seems to be coupled to a gross thickening of the sialic crust with time and is related to the start of plate tectonics (Engel, et al, 1979).

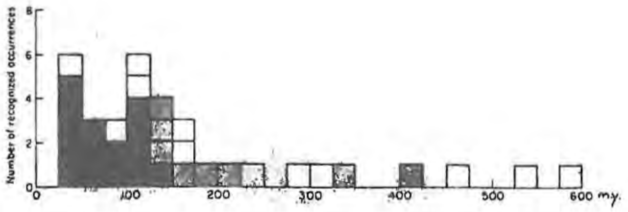


FIGURE 34: Histogram showing the incidence of blueschists with contrasting mineral assemblages with time. Open boxes : epidote-bearing glaucophane schists. Grey boxes : lawsonite ± epidote. Black boxes : jadeitic pyroxene and quartz (from Ernst, 1972).

Plate tectonics, represented by Mesozoic large-scale crustal separation and the subduction of lithopheric plates is a geodynamic process in which plate accretion and subduction are separate tectonic episodes and are not part of the same tectonic cycle. If plate tectonics can be projected back into the Palaeozoic, there should be no correlation of features or trends on the cratons on either side of an orogenic belt. Further extension of processes into the past would mean even more fragmentation and a random assemblage of rocks in all the continental blocks. However, this is often not the case, as matching features, which can be Archean or Proterozoic in age, are developed on either side of major Pan-African Orogenic Belts. In Nigeria the mineral ages of rocks associated with the Pan-African Belt show a symmetrical decrease towards the centre of the belt from the adjacent West African and Congo Cratons, and not an asymmetric pattern that would be expected if plate tectonics had been operative. Earlier orogenic belts in the adjacent cratons were re-foliated and have whole rock Rb/Sr ages that have been lowered in a scattered fashion (Hurley, 1972). The symmetrical decrease in Rb/Sr ages implies that the Pan-African Belts formed in situ and that the gradual decrease and concentration of late-stage magmatic and thermal activity in the centre of the belt was due to a gradual decay of the underlying mantle diapir.

The formation of extensive calc-alkaline volcanic arcs and arches in the Palaeozoic and the later generation of oceanic crust in back-arc basins in the Tasman Geosyncline, on the east coast of Australia, and the Cordilleran Belt, on the west coast of North America, suggest that decoupling of the ocean - continental margins around the Pacific Ocean took place before the break-up of Gondwanaland and Laurasia. In the Tasman Geosyncline profuse calc-alkaline volcanism started in the Late Ordovician and continued into the Mid Silurian. In the Late Silurian and Early Devonian extreme horizontal extension took place resulting in the formation of new oceanic floor, probably in back-arc basins. The development of the Tasman Geosyncline was terminated in the Late Devonian during the Tabberabberan Orogeny associated with syn- and post-tectonic Carboniferous granite plutonism (Schieber and Markham, 1976). The distribution of the volcanic and sedimentary facies, which are characterized by marked lateral facies variations, suggests that the Tasman Geosyncline formed in response to the initiation of subduction along the eastern margin of the Australian Craton. The initial calc-alkaline volcanic activity, the development of oceanic crust in back-arc basins and subsequent collapse, orogeny and granite plutonism suggest that the activity occured in response to the formation of a mantle diapir, probably initiated by the subduction of the Pacific Plate. The Cordilleran Belt shows a similar development to the Tasman Geosyncline (Fig. 36) and is also characterized by a major period of deformation and the thrusting of oceanic and slope sediments over the continental margin deposits during the Late Devonian-Mississippian. Uplift, erosion and the deposition of thick clastic wedges in successor basins was the final consequence of the Antler Orogeny. This was the first time in the development of the Cordilleran Belt that clastic detritus was shed eastwards onto the craton (Windley, 1977). During the Antler Orogeny and subsequent orogenies a number of ophiolite complexes were obducted onto the continental margin. These ophiolite complexes are characterized by a complex pattern of Rb/Sr ages that includes a large number of Precambrian ages. This is significant as it indicates that the Pacific Plate existed as an oceanic plate in the Precambrian and that it was only first obducted during the Antler Orogeny in the Late Devonian.

The definite tectonic inactivity along the west coast of North America during the Late Proterozoic and Early Palaeozoic as indicated by the development of a thick wedge of continental margin sediments, that is in all respects identical to the wedges developed on passive Atlantic-type margins during the Mesozoic. This illustrates that subduction along the west coast of America did not occur until at least the Mid Palaeozoic. The start of subduction in the Ordovician could be coupled with the development of an active mid-ocean ridge within the Pacific Plate, but also could just as easily be associated with the movement of the American Craton over the Pacific Plate in response to active horizontal extension associated with the formation of oceanic crust in the ensialic Palaeozoic Geosynclines. The time of formation of the Ordovician ophiolite complexes coincides closely to the initiation of subduction in the Circum-Pacific Belt.

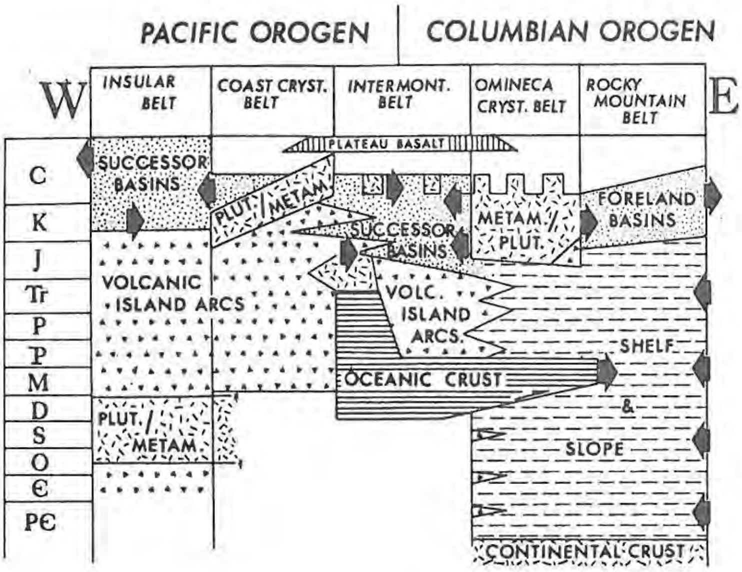


FIGURE 35: Tectonic chart summarizing the evolution of the Canadian Cordilleran Geosyncline (from Thompson and Panteleyev, 1976).

THE MESOZOIC AND CAINOZOIC

The Mesozoic and Cainozoic are characterized by extreme horizontal extension with the generation of oceanic crust and associated wide-spread continental separation. The generation of new oceanic crust has resulted in the development of large lithospheric plates that are bounded by tectonically active or passive margins. Subduction zones mark destructive zones where oceanic crust is forced below continental crust, or active volcanic arcs in response to the generation of new oceanic crust in accreting plate margins. The difference between orogeny at the Mesozoic and Cainozoic and that of the Palaeozoic and Proterozoic is that the initiation of oceanic basins and orogeny are no longer both directly associated with the development and eventual decay of a single mantle diapir. Although rifting, basin development and subsequent horizontal sea-floor spreading are directly associated with mantle diapirism; orogeny and metamorphism is associated with subduction and so is indirectly related to the original mantle diapir. As a result there is an increasing variety and differentiation of tectonic processes and the loss of importance of geosynclinal processes even though segments of the geosynclines can be recognized within the parts of the plate tectonic.

The Mesozoic-Cainozoic Orogenic Cycle, defined by the 75000km long Alpine and Circum-Pacific Orogenic Belts is a mega-episode of diverse sedimentation, the emplacement of batholiths and mountain building.

Activity has continued with varying intensity along segments of the belt since the Early Triassic. The Mesozoic-Cainozoic orogenic belts are not randomly distributed, but in a general way follow an orthogonal pair of great circles (Fig. 36). The Circum-Pacific Belt tends to mark the border between the Pangea-like concentration of continental plates with a hemisphere-sized ocean. The Circum-Pacific Belt evolved largely at, or subparallel to the interface between older continental crust and oceanic crust, while the Alpine Belt formed largely between colliding continental crust (Engel and Klem, 1972). In the Circum-Pacific Orogenic Belts the constituent igneous rocks are dominated by relatively unfractionated andesites and quartz-diorites, while the associated sediments are largely tuffaceous wackes that are less mature and less dominated by continental components than those of the Alpine Orogenic Belt. The voluminous piles of poorly fractionated volcanics and intrusive plutons, as well as immature tuffaceous wackes, developed within the Circum-Pacific Orogenic Belt have more in common with the Archean Greenstone Belts than with the Proterozoic Geosynclines.

The Circum-Pacific Orogenic Belt contains a large number of paired

FIGURE 36: A Permian pre-drift map of the continents showing the development of Phanerozoic Belts along two orthogonal great circles on the margins and within the Proterozoic mega-continent (from Windley, 1977).

metamorphic belts that contain adjacent high-pressure low-temperature Blueschist facies metamorphic rocks and intermediate-pressure high-temperature Barrovian facies metamorphic rocks (Windley, 1977). The Blueschist facies metamorphic belt is characteristically developed in the oceanic side and reflects the effect of subduction on the geothermal gradient. The reduction in the geothermal gradient is in response to the down-going of relatively cool lithospheric plates, that are commonly a significant distance away from their origin at the mid-oceanic ridges, which are characterized by high heat flow. As a result orogenic deformation marginal to the subduction zones is not associated with high heat flows characteristic of the geosynclinal orogenic belts. The presence of adjacent Barrovian metamorphic belts, commonly associated with calc-alkaline volcanic and plutonic activity, suggests that the subduction process might initiate a secondary mantle diapir, in response to shearing in the mantle during the descent of the lithospheric plates into the mantle. High thermal gradients correlate strongly with zones of high seismic activity. The high thermal gradients associated with mid-oceanic ridges can be directly related to mantle diapirs. The high heat flows that occur above Benioff Zones however are in contrast to the idea that the down-going plate would bring about a region of low heat flow and suggests that subduction initiates a secondary mantle diapir.

The rupturing of continental crust and sea-floor spreading is not a rapid event, but is rather the culmination of a long history of epicontinental tectonism. Per-alkaline volcanism characteristically accompanies thermal arching that preceeds and accompanies incipient rifting. The volcanism is concentrated near the crest of the broad domal uplifts, which appear to be spaced at intervals of roughly 1000-2000km along the trend of the developing rift belt. When sufficient crustal extension affects the arched regions, grabens and half grabens develop in response to rifting and normal faulting in the crest of the domes. These rift valleys become filled with continental sediments intercalated with volcanics. Progressively 250-500km wide regions on either side of the rift valleys are subjected to further extensional normal faulting (Dickinson, 1974).

With increased volcanic activity, dyke injection leads to continued horizontal extension with the formation of simatic crust and associated continental drift. As the continents drift apart, the aseismic continental margins would slowly subside and become the sites of the accumulation of continentally-derived sedimentary wedges composed essentially of miogeosynclinal-type sedimentary assemblages.

Studies of modern day active rift systems have given considerable insight into the tectono-sedimentary evolution of rift systems and have resulted in the development of models, which can in turn be applied to older examples. As a result, it is necessary to examine some of the features of more recent and presently active rift systems. The initial stages of rift development and the proto-basin stage are best illustrated by the presently active East African Rift-Red Sea System. The Basin and Range Province in America appears to be a good example of a major rift-controlled ensialic basin, while the late stages of crustal separation and the formation of simatic crust are best illustrated on the Mid-Atlantic Ridge in Iceland.

The East African Rift-Red Sea System

The East African Rift System forms a NNE-SSW tending 4000km zone, from Asmara near the Red Sea to the Zambezi and attains a maximum width of 1000km in Tanzania (Fig. 37). The rift system consists of a series of discontinuous true grabens and half grabens which are characterized by differential uplift, normal faulting and alkaline volcanisity (Fig. 38). The rift system has been periodically active since the Jurassic although the pattern of the rift system is found to reflect Precambrian basement structures (McConnell, 1967). Many of the rifts are, however, physically discontinuous. The Kenyan Rift Valley forms a single tectonic unit that is characterized by an extension about 10km in the centre that decreases to 3km or less at the northern and southern extremities. The age of rifting also differs from province to province, as the southern province was active chiefly in the Mesozoic, while the rifts in the northern province formed at different times in the Cainozoic. The Lake Malawi Rift, a reactivated Cretaceous rift, provides a link between the Miocene and Pliocene East Africa Rift System, and the Jurassic and Cretaceous structures formed contemporaneously with the breakup of Gondwanaland (Burke and Dewey, 1973).

A study of the warping of Mesozoic and younger erosion surfaces has showed that there is a close relationship between areas of domal uplift and provinces of per-alkaline and alkaline magmatism. These swells of the continental crust occur as independent centres of the order of 500-1000km across, with an increased elevation of about 1000m (Fig. 39).

FIGURE 37: Map of the main features of the East African Rift-Red Sea System, illustrating the influence of early structures on rifting and graben formation and the alignment of the Trompsberg (T) Bushveld Igneous Complex (B) and the Great Dyke parallel to the trend of the Ethiopian Rift (from McConnell, 1974).

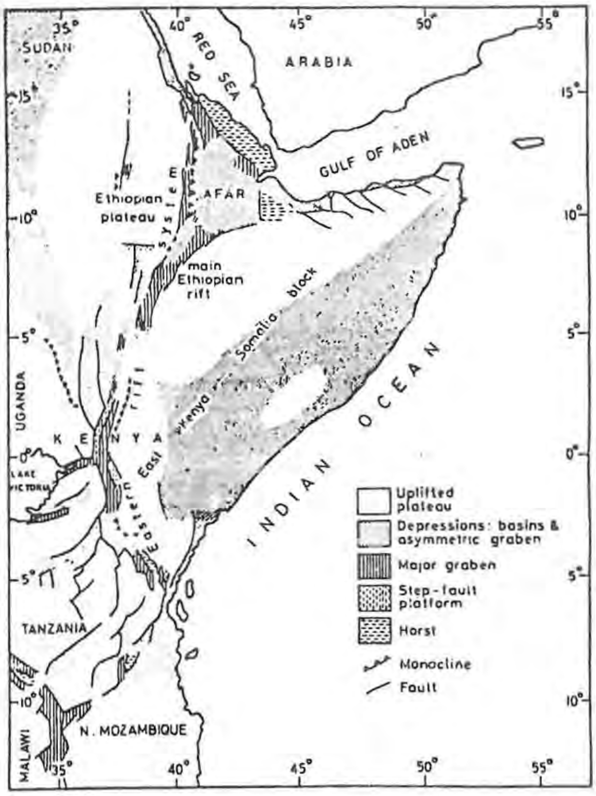


FIGURE 38: The main structural elements of the Eastern Branch of the East African Rift System (from Baker, et al, 1972).

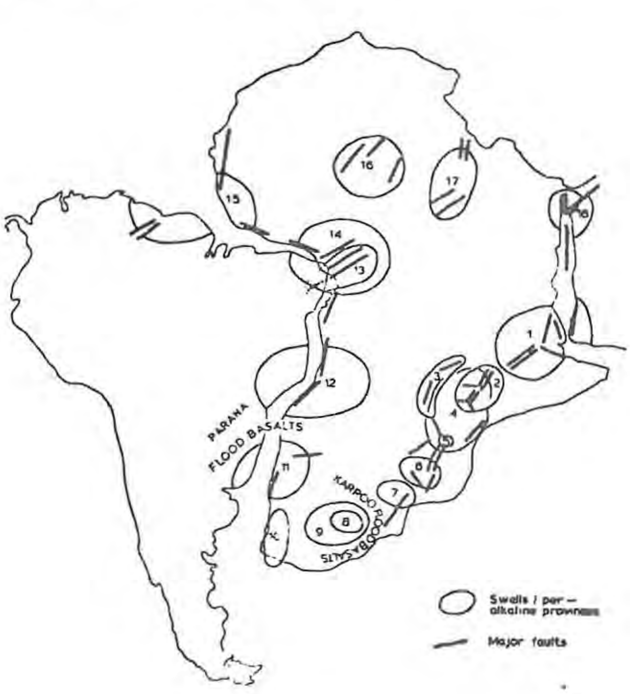


FIGURE 39: Sketch map of the domical uplifts and per-alkaline igneous provinces that have developed in Africa and South America since the Late Palaeozoic. The superposition of major faults illustrates the random patterns of rifting associated with the domical uplifts (from Le Bas, 1971).

These domal uplifts are generally transected by rifts and associated graben structures that may assume a linear or radiating pattern, depending on the grain of the basement (Fig. 40) (Le Bas, 1971 and Baker, et al, 1972). The presence of areas of uplifted and eroded Precambrian basement along the rift margins indicates that the rate of uplift and erosion of the domes is greater than the accumulation of the volcanics on these plateau areas. Uplifted terrains of Precambrian basement are also prominantly developed along the African and South American Coasts while extensive intra-cratonic basins, filled by Mesozoic strata, occur on both cratons indicating that the proto-Atlantic rift was also characterized by arching during the Jurassic (Fig. 39) (Dickinson, 1974).

Although the Rift System has an overall NNE-SSW axis the strike directions of individual components varies from NW-SE to ENE-WSW. The different segments of the rift system often have a close association and parallelism with Precambrian mylonite and migmatite zones (Fig. 37). This close association is best illustrated by the dividing of the rift system into the Eastern and Western Rifts round the resistant Tanzanian Craton. The Western Rift is subdivided into four straight segments that swing around the Tanzanian Craton. The Albert and Edward Rifts follow the trends of Archean and Early Proterozoic (Ubendian) orogenic belts, which is now marked by a 100-150km wide belt of refoliated basement with associated migmatites and anetectic granites. The Gregory and Ethiopian Rifts of the Eastern Branch follow the meridional strike of the Mozambique Orogenic Belt although individual faults cut across foliation trends and even cross the Mozambique Front. The Luangwa Rift Valley follows the Irumide Trend which continues along the Kariba Fault into the Okavango Rift System. The Luangwa Rift Valley is largely filled with Karoo-age sediments but was also rejuvinated during the Cainozoic. The strike of the Gregory Rift is aligned along a major NNE-SSW lineament that extends through the ±2600my Great Dyke, situated in the Rhodesian Craton. This line continues south through the 2000my Bushveld Igneous Complex and the 1300my Trompsberg Igneous Complex (Fig. 37). The Bushveld Complex is localized by the intersection of the NNE-SSW trend with the Murchison Lineament, which is a major linear that controlled the sedimentation of the Transvaal Supergroup. The Trompsberg Complex is situated where the NNE-SSE linear intersects the margin of the Grenville-age Namaqua-Na al Orogenic Belt. These three major igneous complexes represent periodic thermal activity along this major NNE-SSW tending Archean lineament through time

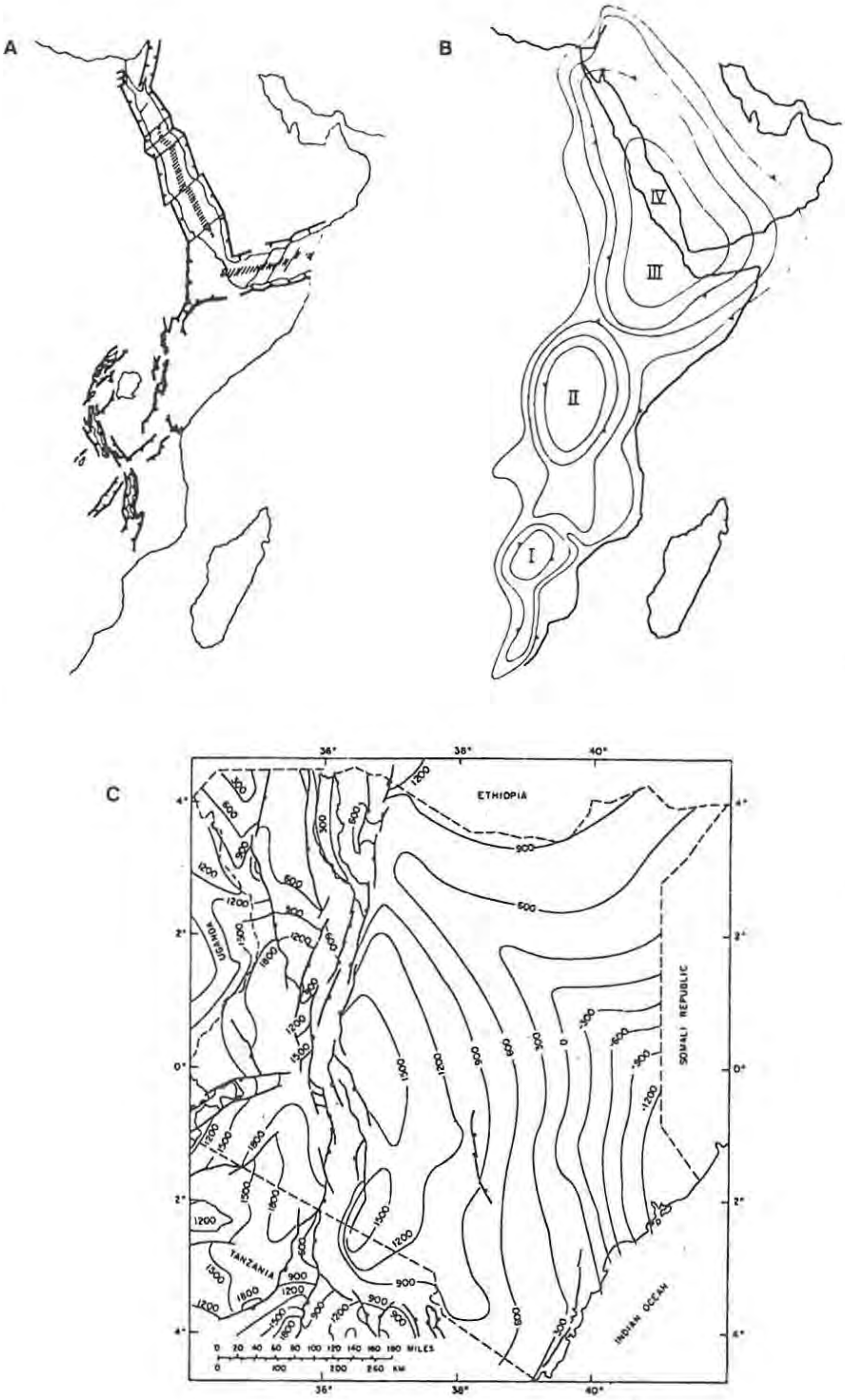


FIGURE 40: The extent of crustal uplift and dome formation along the East African Rift-Red System. (A) The main features of the rift system; (B) Outline of the major crustal uplifts with contours drawn at about 1km intervals. The (I) Rhodesian; (II) East African; (III, IV) Nubian-Arabian Domes. (C) Detailed map shows the isobases of the pre-Miocene erosion surface in Kenya (from Degens and Ross, 1976 and Baker, et al, 1972).

which is significantly localized at the intersection of major transverse lineaments. Elongate Karoo-age sedimentary troughs trend round the Rhodesian Craton along the Zambezi and Mozambique Belts in a similar fashion to the splitting of the Eastern and Western Rifts around the Tanzanian Craton. The Okavango Rift System, which is still active today, follows the early Irumide and Damaran trends (Fig. 37), which also illustrates that major taphrogenic lineaments have been periodically reactivated through time.

The Red Sea, Gulf of Aden and Ethiopian Rift intersection in the Afar Triangle is often referred to as a classic triple junction (Burke and Dewey, 1973). However, this junction has been shown to have developed along three major intersecting lineaments (McConnel, 1974). The Red Sea trend does not terminate in the Afar Triangle but continues through into Somalia where it is characterized by major faults associated with the development of the Asseh and Nogal rift-bounded grabens (Fig. 37). Although the NNE-SSW trend of the Ethiopian Rift is cut off abruptly by the Red Sea trend in the south-west corner of the Afar Triangle its continuation is still manifested in the Arabian Peninsular by the Aden Volcanics. Even though the spreading ridges of the Gulf of Aden are orientated east-west they are offset by NNE-SSW transform faults, which gives the Gulf of Aden an apparent ENE-WSW trend. The east-west trend continues as a linear zone of seismic epicenters and magnetic anomalies across the Afar Triangle (McConnell, 1974).

The continuation of the Red Sea, Gulf of Aden and Ethipian Rift Systems across the triple junction indicates that these rifts are a result of the reactivation of earlier taphrogenic faults. The tranform faults in the Red Sea also correlate with Precambrian facture zones on the adjacent continents. These features suggest that major doming associated with mantle diapirism would lead to the reactivation of early lineaments (rifts), which in turn might control further lateral spreading of the mantle diapir. Mantle diapirism therefore either leads to the generation of classic central grabens as for example the Rhine Valley, (Fig. 41) or to the reactivation of existing linears and the formation of irregular triple and quadruple junctions in the crestal zones (see Fig. 39). The reactivation of existing linears is particularly well illustrated by the geometry of the rifts associated with the East African Dome centred on Lake Victoria. The Western and Eastern rifts are in fact developed on the margins of this uplift due to the preferential reactivation of Precambrian zones of

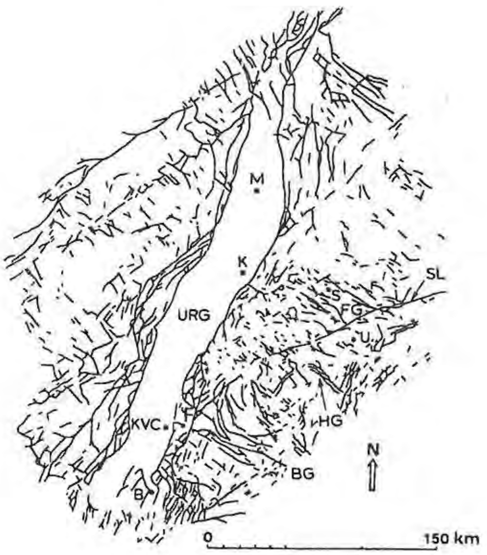


FIGURE 41: Fault pattern of the Rhine Graben illustrating the development of a classic central graben that changes into fan-shaped troughs on the extremities of the domical uplift. North-east south-west trending faults are reactivated older lineaments (from Withjack, 1979).

weakness around the stable Archean Tanzanian Craton (Fig. 40).

The major volcanic episode in the Africa Rift System is illustrated by the profuse eruption of the Trap Series fissure basalts along the Ethiopian and Kenyan Rift Valleys (Fig. 42). This volcanic episode was initiated in the Eocene-Oligocene, in the vicinity of the Afar Triangle to the north and progressively extended to the south during the Oligocene. The flows thicken and increase in number from a thin sequence a few hundred metres thick on the plateaus, to greater than 2000m within the Ethiopian Rift Valley. This volcanism, coeval with the start of volcanism in the Red Sea Gulf of Aden area is the result of continued horizontal extension in the crestal region of the domal uplift. The later Miocene and Pliocene volcanism in the East African Rift System is in contrast confined to the intersections of major rift segmen or the intersection of taphrogenic transverse linears with the rift valleys. The volcanism is dominantly per-alkaline and alkaline with an abundance of alkali basalts that are typically grouped into provinces centred on regions of crustal swelling (Le Bas, 1971).

The Red Sea Rift was initiated in the Early to Mid Tertiary by uplift along a major axis of upwarp that in the Early to Middle Tertiary was accompanied by normal faulting and by structural failure further to the

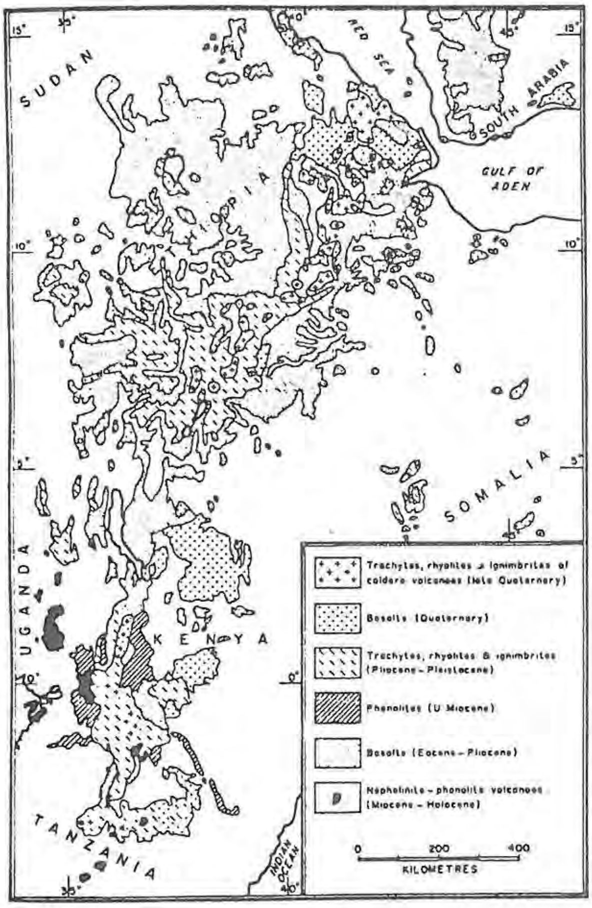


FIGURE 42: Distribution of the main volcanic groups of the Eastern Rift zone of the East African Rift System (from Baker, et al, 1972).

west along a narrow zone parallel to the axis (Hallam, 1972). Following the doming and rifting, volcanicity started in the Oligocece (±30my) and has continued to the present. In the Miocene the normal faulting to the west to the central rift formed the Danakil Alps (Fig. 43). The easterly down-thrown block on the coastal plain became the site of deposition of thick evaporites and other sediments in the Miocene as the basement subsided asymmetrically with the development of a westerly tilt. The extensive extrusion of lavas and pyroclastics took place along this zone of tension (Hallam, 1972). Having been intermittently marine since the Eocene, the Red Sea became permanently marine in the Late Miocene. The same pattern of faulting and asymmetrical subsidence was repeated further west in the Pliocene to create the Ethiopian Plateau and Danakil Depression (Fig. 43), illustrating that the zone of crustal extension became progressively wider with time. During the Late Pliocene (±3,5my) the profuse extrusion of tholeiitic lavas and dyke injection caused further horizontal extension and the separation of the continental crust

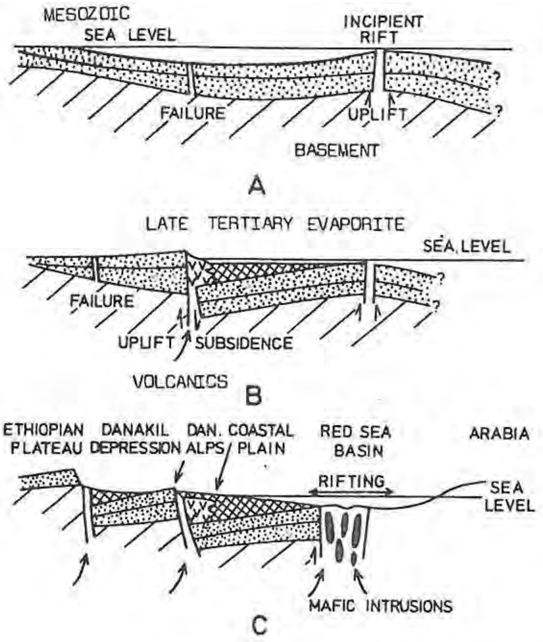


FIGURE 43: Schematic cross-sections illustrating the evolution of the Southern Red Sea and Afar region (A) Eocene-Oligocene; (B) Early Miocene; (C) Late Miocene to Quaternary (from Hallam, 1972).

with the formation of oceanic crust in the centre of the Red Sea (Fig. 43) (Scrutton, 1973).

The central rift valley in the oceanic crust in the median zone of the Red Sea is characterized by high heat flow due to the presence of a sub-crustal mantle diapir, indicated by seismic observations, that extends laterally beneath the present extent of the Red Sea (Fig. 44) (Ramberg, 1971). Rise of this mantle diapir initiated the development of a major dome that reactivated three important Precambrian lineaments. Progressive horizontal extension associated with the development of the Nubian-Arabian Domes led to profuse volcanic activity in the Oligiocene. Due to space constraints in the global plate system only two of the three rifted arms continue to be zones of further horizontal extension. Progressive crustal thinning eventually led to intense tholeiitic volcanic activity in the central rift valley with the subsequent development of simatic crust and the separation of the continental crust. In the relatively inactive East African Rift System alkaline volcanism was confined mainly to the intersections of major rifts.

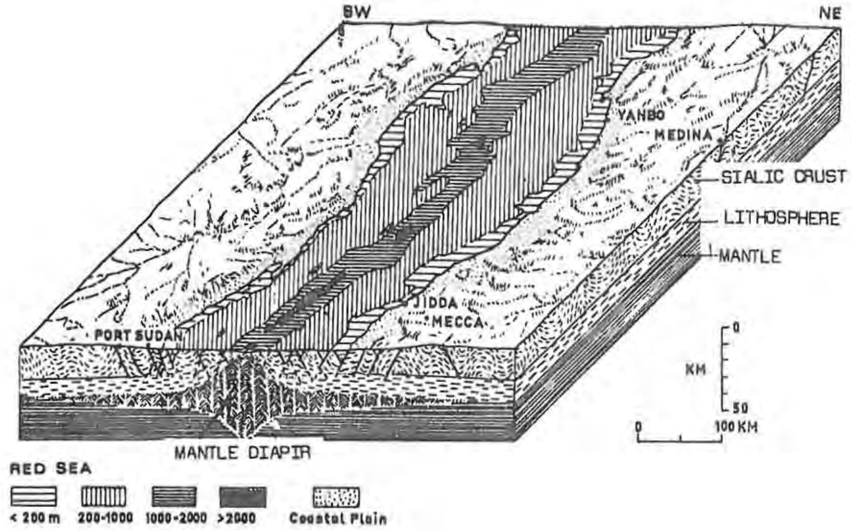


FIGURE 44: Block diagram of the topography of the Red Sea region and the development of an anomalous mantle diapir centered on the Red Sea Rift Valley (from Remberg, 1971).

The Basin and Range Province and The Rio Grande Rift

The Great Basin is a 700km wide zone of nearly evenly spaced semi-parallel NNE-SSW trending mountain ranges that are bounded on one, or on both sides by steeply dipping normal faults (Fig. 45). The Great Basin corresponds to a well defined zone of high heat flow, thin crust and anomalously high attenuation of low velocity seismic waves in the upper mantle. Seismicity of predominantly normal-type is concentrated in the two marginal zones, which are also the zones with the most recently volcanic activity. The continental crust is approximately 30km thick below the Great Basin and increases abruptly to greater than 40km thick on the boundary with the Colorado Plateau on the east, and the Sierra Nevada on the west (Fig. 46). The depth to the top of the low velocity zone, which extends to a depth of 150-170km, increases abruptly from 30km to 100km at the Great Basin - Colorado Plateau transition. The presence of high heat flow and a general low Bouguer gravity anomaly suggests that a mantle diapir exists below the Great Basin (Scholz, et al, 1971).

Faulting began in the Eocene to Oliocene, although most of the deformation and crustal extension has occured since the Miocene. Estimates of crustal extension range from 50-300km. The faulting is uniformly normal, except on the western margin where there is some right-lateral strike-slip faulting. Wide spread intermediate composition calc-alkaline volcanism began in the Early Oligocene in the south-eastern part and progressively

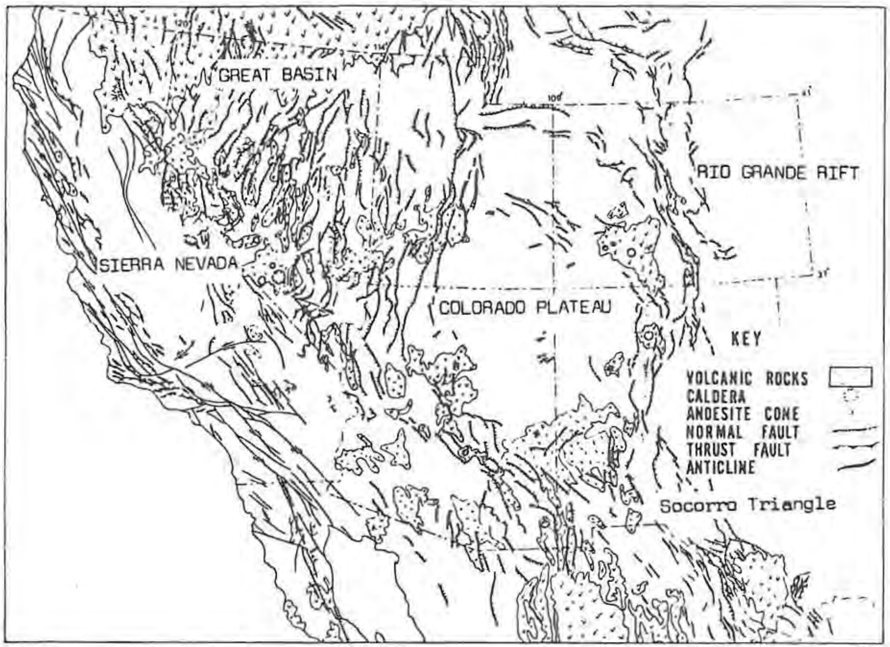


FIGURE 45: Map of the western coast of North America illustrating the tectonic setting and in particular the distribution of normal faulting and volcanic activity in the Great Basin, the Basin and Range Province, the Colorado Plateau and the Rio Grande Rift (from Ramberg and Newman, 1978).

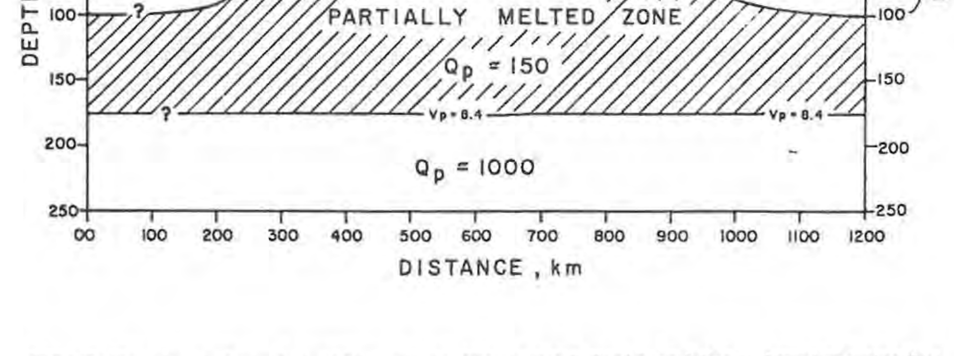


FIGURE 46: An east-west section across the central Basin and Range Province showing the ages of silicic volcanism, and the structure of the sialic crust and upper mantle (from Scholtz, et al, 1971).

moved northwards and also spread laterally outwards from a central core during the Miocene, Pliocene and Quaternary. As a result, there are successively larger rings of younger igneous rocks with the youngest located on the margins. The rate of outward migration has been asymmetric, in that it has been more rapid to the west. Recent volcanic activity is associated with the seismically active marginal zones (Fig. 46) (Scholz, et al, 1971). The erruption of the andesitic volcanics blanketed the area with volcanic flows and breccias until the period from 12,5my-7,5my when the area became an intergrated depositional basin. Approximately 2500m of sediments accumulated in the basin, which reached its maximum extent at approximately 10,5my. The sedimentary facies varied from fluvial to lacustrine. At approximately 7,5my the region was disrupted by NE-SW normal faulting into the existing structural blocks. During a relatively quite tectonic period a well defined erosion surface developed. This erosion surface was locally covered by basaltic volcanic flows and rhyolitic domes that were commonly emplaced along faults. Broad upwarping and renewed block-faulting during the Quaternary produced the present topography (Gilbert and Reynolds, 1973).

Uplift and andesitic volcanism started 40my ago over most of the Basin and Range Province, which is situated immediately east of the Cretaceous-age granites of the Sierra Nevada that had formed in association with an easterly dipping subduction zone. The area was therefore in a largely compressive stress field behind the subduction zone so that volcanism could only occur by forceful injection. As a result, the volcanism was restricted to hydrous calc-alkaline magmas, which could achieve fluid pressures in excess of the regional stress field. In the Late Cainozoic there was an abrupt change in style from the calc-alkaline to basaltic volcanism, due to a release of the regional stress 25my ago by the annihilation of the Mid-Tertiary oceanic ridge in the subduction zone. Extensive normal faulting was associated with the basaltic volcanism and progressively expanded towards the east as the triple junction moved northwards until the complete termination of the subduction zone approximately 10my ago.

The evolution of the Basin and Range Province can be related to a mantle diapir that developed approximately 40my ago and spread out progressively with time causing periodic normal faulting, crustal extension, coeval volcanism and the development of a broad local sedimentary basin and subsequent uplift and decay of activity. The Basin and Range Province can therefore be thought of as an ensialic inter-arc basin (Scholz, et al, 1971). A possible reason why the most intense volcanism always occured at the outer margins of the diapir might be due to the production of strong tensional forces along the boundary between the outflowing mantle diapir and the adjoining areas of thicker lithosphere. As the margins of the diapir spread out beneath the lithosphere, the interior zone might have become less active due to the loss of its lower melting fraction, so that surface volcanism died out.

In the San Juan volcanic field, to the north-east of the Rio Grande Rift, olivine andesites are the earliest volcanics and were followed by voluminous alkali-andesite, rhyodacite and quartz-latite volcanics that were erupted from numerous central volcanoes. The partitioning of trace elements in the alkali andesite liquids was controlled by a garnet-clinopyroxene assemblage in which plagioclase and olivine were sparse, indicating that the equilibration of the alkali-andesite magma took place at high pressures, above that of the stability of plagioclase and therefore at lower crustal depths. Trace element distributions also indicate that the more felsic volcanics were generated by fractional crystallization of plagioclase and lesser hornblende (±biotite) from an alkali-andesite at low pressures (Zielinski and Lipman, 1976). It would therefore appear that the alkali-andesites were generated in response to the interaction of alkali-basaltic magmas,probably derived from a mantle diapir, with lower sialic crust. These magmas equilibrated and then rose through the crust and subsequently underwent differentiation at shallow crustal levels to produce the more felsic volcanic derivatives.

Large magma chambers of the cauldron-type appear to induce the formation of local depressions in response to collapse following the extrusion of lavas (Heiken, 1976). In Northern California the Shasta Valley Depression is a 100km diameter circular structure that contains Pliocene and Holocene lavas and pyroclastics. There is a difference in elevation of 1000m between the floor of the depression and Miocene-Pliocene erosion surface above the adjacent arcuate scarp. A coincident negative Bouger anomaly is thought to represent the presence of a low density melt at a depth of 4-10km. In the Shasta Valley Depression the density of volcanic vents is approximately four times greater in an area where the depression is intersected by a zone of normal faults of the Basin and Range Province (Heiken, 1976). The presence of linear zones of volcanic vents also suggests that the volcanism is controlled by the faults. The nature of the volcanism also changes dramatically; differentiated felsic volcanics are dominant in the poorly faulted zones while mainly basaltic volcanics and some dacite flows occur in the more intensely faulted area (Heiken, 1976).

The Rio Grande Rift is developed along the boundary between the Colorado Plateau on the west and the mid continental craton on the east. When regional extension reactivated the Southern Rocky Mountains rifting began between 32-27my on a major northerly-trending zone of weakness that had developed during the Late Palaeozoic and Late Cretaceous-early Tertiary orogenies. Adjacent to the uplift along the Rio Grande Rift shallow basins were filled by mafic flows and volcanic ash beds intercalated with alluvial fill. As the rift opened it broke en-echelon across a series of NE and WNW trending lineaments in the basement terrain to form six northerly-trending basins with lateral displacements of up to 55km (Kelley, 1977). The taphrogenic transverse structures tend to be zones of high heat flow and geothermal activity and zones of volcanic activity. A large present day sill-like magma body, which exists at mid-crustal depths of approximately 19km, ends abruptly against one of these transverse structures and is apparently leaking magmas along it to form shallow magma reservoirs.

The Main Rio Grande Rift is divided into three segments. The northern segment follows the NNW trend of the Late Palaeozoic and Laramide (45-75my) structural grain and is characterized by a near absence of syn-rift volcanism in the axial basins. The rift is characterized by a shift in horizontal extension away from the axial grabens into a broad belt along the shoulders. The axial graben tapers northward and pinches out into a broad zone of block faulting. The central segment consists of a series of en-echelon basins separated by complex transverse structures. The southern segment has undergone the most extension and widens into a northerly-trending series of parallel basins and ranges with a total width approximately three times that of the large single rift valleys to the north. The rift also separates into the weaker San Augustin Rift that extends south westerly along the Morenci lineament. Between the San Augustin Rift and the southern segment of the main rift is a triangular area, approximately 80km on each side, which has undergone moderate (±50%) crustal extension, normal faulting and horst and graben formation, as well as voluminous early rift and late rift volcanism. Large volumes of basaltic andesite, and rhyolitic ash-flow sheets, with high initial ratios and therefore a lower crustal origin developed in localized area between

32my and 20my. This was followed by a Middle Miocene lull (20-12my) after which volcanism slowly increased and became concentrated in the Socorro Triangle and Jemez Mountains where the rift transects major north-easterly trending linaments. Associated with the increase in volcanic activity the volcanism changed to bimodal basalt-rhyolite, with low initial ratios indicating that the horizontal extension and the increased volcanism was a response to mantle diapirism.

The three different segments of the Rio Grande Rift illustrate some of the features of the progressive development of a rift system. Early rifting is associated with uplift, rifting and graben formation and minor volcanism. Further horizontal extension caused normal faulting to occur on the shoulders of the domical uplift that would eventually become a series of horst and graben structures. Continued horizontal extension developed faults that penetrated through the crust and acted as permeable zones for mantle-derived tholeiitic volcanism. Eventually further horizontal extension would lead to the development of broad basin on the scale of the Great Basin. Subdued tectonism during this pivotal stage would allow the development of an extensive sedimentary sequence. Tectonic reaction then would disrupt this sedimentary style and cause block-faluting, minor volcanism and erosion of the uplifted horst blocks. The Great Basin has undergone a full cycle of development and is now in the destructive stage associated with a decaying mantle diapir.

Sea-Floor Spreading and the Development of Continental Margins

On a global scale the Late Mesozoic continental separation was the final episode of continued subsidence and basin development peripheral to ancient blocks,that started in the Late Palaeozoic. In Gondwanaland at least, it is evident that the Mesozoic continental margins developed along the trends of ancient taphrogenic faults and orogenic belts (Kent, 1977). Limited alkaline and tholeiitic volcanism is generally associated with initial rifting and graben development while intense tholeiitic volcanic activity often occurs just prior to or just after the deposition of the first marine sediments in the rifted basins (Fig. 47). Periodic marine incursions into the grabens led to the formation of thick evaporite units on top of the predominantly continental sandstones. The period of intense tholeiitic volcanic activity usually spans between 30-40my and is the response to thinning of the continental crust with progressive horizontal extension. The profuse lava extrusion and dyke intrusion eventually led to continental breakup and sea-floor spreading. Breakup sometimes occurs at the onset of the intense igneous activity but generally occurs, typically ±25my, after the start of profuse volcanic activity (Scrutton, 1973). The onset of sea-floor spreading generally led to a decrease in volcanic activity and the establishment of fully marine conditions.

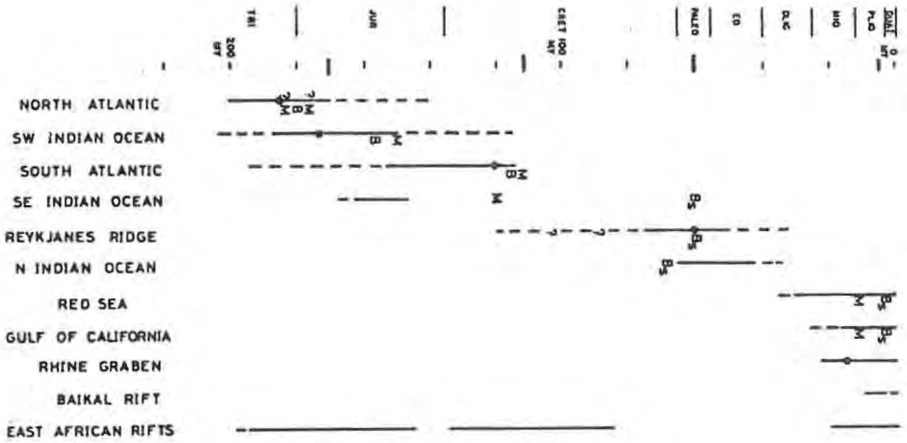


FIGURE 47: A summary of the data relevant to continental breakup during the Mesozoic: ———— 0 ———— Duration of igneous activity with peak if known; - - - - - - - Possible continuation of activity; B : Time of continental breakup; M : Earliest marine sediments (from Scrutton, 1973).

The North Atlantic began opening up in response to sea-floor spreading at about 180-170my ago with the separation of North America from north-western Africa (Fig. 48). During the Upper Cretaceous the Labrador Sea opened and finally spreading switched to the presently active Reykjanes Ridge at approximately 60my. On the adjacent continents, coeval igneous activity was associated with the initial phase of spreading and also with the switch to the Reykjane Ridge, while a period of rapid intra-Cretaceous continental sedimentation was associated with the opening of the Labrador Sea (Scrutton, 1973). The separation of Africa and South America took place between 120-112my at about the same time that the Labrador Sea opened. Although the differential opening of the major oceanic basins occured diachronously, there appears to be a definite periodicity in the continental fragmentation, with major peaks at about 170my, 115my, 60my and 4my (Scrutton, 1973). The onset of volcanic activity associated with initial continental rifting seems also to be synchronous in different parts of the globe. The initiation of rifting in different parts of the globe would also be expected to cause a re-orientation of the global rigid lithospheric plates. Some of the ages of continental separation correspond to major re-orientations of the oceanic plates (Vogt, 1975), indicating that sea-floor spreading is not a random process but is controlled by major geodynamic processes in the mantle.

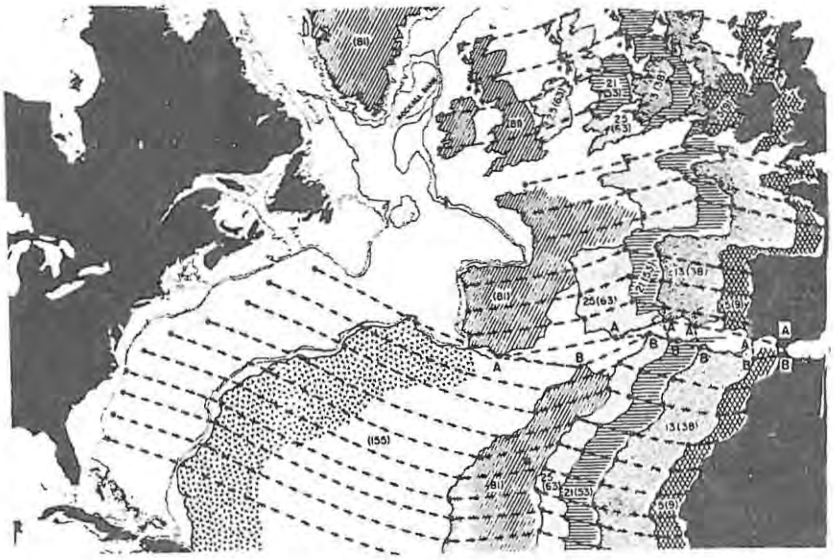


FIGURE 48: The relative positions of Europe and Africa relative to North America at specific times during progressive sea-floor spreading (from Pitman and Talwani, 1972).

Sea-floor spreading involves the symmetrical generation of oceanic crust in an active mid-oceanic ridge. The processes operative during sea-floor spreading are best understood from studies carried out in Iceland, a major volcanic island situated on the axial zone of the Mid-Atlantic Ridge. Recent volcanic activity in Iceland has been confined to an active belt between 30-50km wide,with the maximum intensity of activity moving at random across the whole width of the zone. Open fissures, emissive fissures and normal faults are the major kinds of parallel structures that develop within the active zone. The width of the graben structures developed in the active zone range from a few meters to a few tens of kilometers. Extrusion of lava out of the emissive fissures leads to the progressive accumulation of lava flows. With progressive extension the proportion of feeder dykes perpendicular to the lava flows increase with depth and eventually grades into a sheeted dyke complex. The normal faults occur independently of previous lava flows, and are therefore not due to isostatic compensation related to the volume of extruded lava, but represent the surface expression of tectonic extension (Daignieres, et al, 1975).

Continental separation involves the initial development of a transitional crust and lithosphere between the continental fragments and adjacent oceanic basin. Extensional faulting at upper crustal levels, and probably some pseudo-plastic flowage at deep crustal levels, results in attenuation of the continental crust, and the formation of quasi-continental crust (Fig. 49). Sedimentation contemporaneous with volcanism in the initial rift depression would form a complex succession of lava flows, dykes, sills and sediments that would result in the formation of crust with oceanic affinities but unusual thickness, or quasi-oceanic crust (Fig. 49) (Dickinson, 1974).

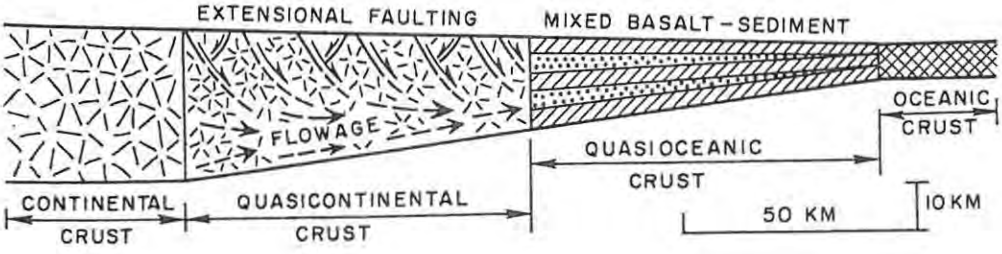


FIGURE 49: Schematic diagram illustrating the development of transitional quasi-continental and quasi-oceanic crust along a rifted continental margin (from Dickinson, 1974).

Some mid-ocean ridges show conspicuous axial valleys (Gorda Rise) while others do not (East Pacific Rise). In intermediate cases the axial valley or graben does not seem to be a continuous structure along strike. The presence of a narrow axial valley is related to the width of the active zone. It is visualized as being associated with a variable size of the "thermal head" of the mantle diapir. If the asthenosphere is close to surface in a narrow wedge the active zone would be narrow, possibly with an associated axial valley. However, if the mantle diapir defined a smooth arc the active zone would be broader so that the plate boundary would be defuse and would not be marked by a major axial valley (Daignieres, et al, 1975). This pattern is remarkably similar to the development of narrow axial grabens associated with initial continental uplift which is then followed by the progressive increase of the zone of normal faulting due to continued horizontal extension associated with lateral spreading of the mantle diapir. Mid-oceanic ridges might also undergo evolutionary changes.

The opening of an ocean by profuse volcanism and dyke injection should be discussed in terms of rigid plates. The relative movement of two rigid plates on a spherical earth can be represented at any given time by movement about a pole of rotation. As the mechanically constraints imposed by the segments of continental lithosphere, when continents first split apart, are much stronger than those constraints imposed by thin oceanic lithosphere produced at a normal accreting plate margin, the plates would rotate about a common pole (Francheteau and Le Pichon, 1972). Rifted zones are often not continuous structures but may be composed of a series of en-echelon rifted segments that are separated by major transverse basement linears. Following progressive thinning of the continental crust those transverse structures that lie close to direction of small circles about the pole of rotation will act as transform faults when spreading starts. These would also form major offsets on the continental margins. During initial rifting the intersection of these transverse structures with the main rift valley were often zones of extensive volcanism. Continued active volcanism would build up marginal fracture ridges on new ocean floor away from the offsets, which would remain as transform fault zones along the mid-oceanic ridge. As the ocean widens by the accretion of new oceanic lithosphere, the sea floor gradually moves away from the thermally active accreting plate margin and so would progressively subside. This is in response to the thermal contraction of a cooling lithospheric plate. The rate of subsidence would be initially ±100mm/my, and would decline with time to ±10mm/my. As a result the oceanic crust beneath a presently active ridge crust occurs at relatively shallow depths of 2,5 - 3,0km below sea level and becomes progressively deeper with age, so that oceanic crust older than 75my occurs at a depth of ±5Km (Dickinson, 1974).

Following initial rifting and the development of a sediment-filled graben further horizontal extension would be expected to lead to profuse volcanic activity. Since the major rifts are developed on the margins of the grabens it might be expected that they would also be the zones of maximum volcanic activity. As a result, the graben would most likely be breached on its margin along the rift rather than, as in most generalized rifted continental margin models, along the axial zone (Fig. 50). Prior to sea-floor spreading the Tasman Sea was an elongate rift valley that was eventually breached along its western flank. As a result on the west the Australian Continental margin shelf is narrow and is underlain by a few hundred meters of uniform, flat-lying sediments and is virtually barren of rift-stage sediments. In contrast, on the eastern side of the Tasman Sea horst and graben structures in the basement reach up to 200km in width and are filled by early continental sediments (Jongsma and Mutter, 1978).

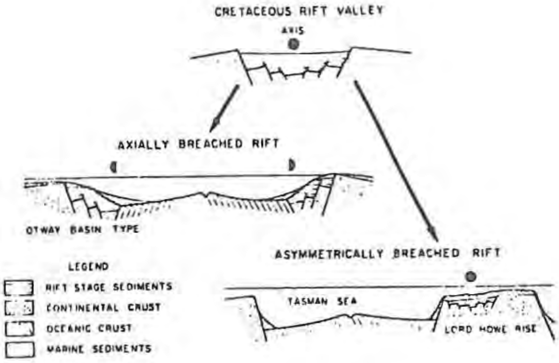


FIGURE 50: Diagram illustrating the result of axial and non-axial breaching of the rift valley during sea-floor spreading (from Jongsma and Mutter, 1978).

Large shallow continental basins often develope on the margins of the narrow uplifts marked by the axial rift valleys. This is well illustrated by the shallow inter-arch basin that is developed between the Western and Eastern Branches of the East African Rift System which is occupied by Lake Victoria. In consequence to sea-floor spreading within one of the rift valleys, a continental inter-arch basin would develop into a rim basin on one of the resulting continental margins. The Western margin of Australia had a configuration of rifted arches and associated marginal basins prior to plate devergence (Fig. 51). Sea-floor spreading is thought to have taken place along one of the boundary faults of a rift. The rim continued to influence the distribution of the depositional facies for 30-40my after breakup, until the rim subsided below sea level (Veevers, 1977).

The development of rifted continental margins results in the juxtaposition of an elevated continental block, with sediment sources, against a newly formed ocean basin that serves as a sediment sink. The floor of the new

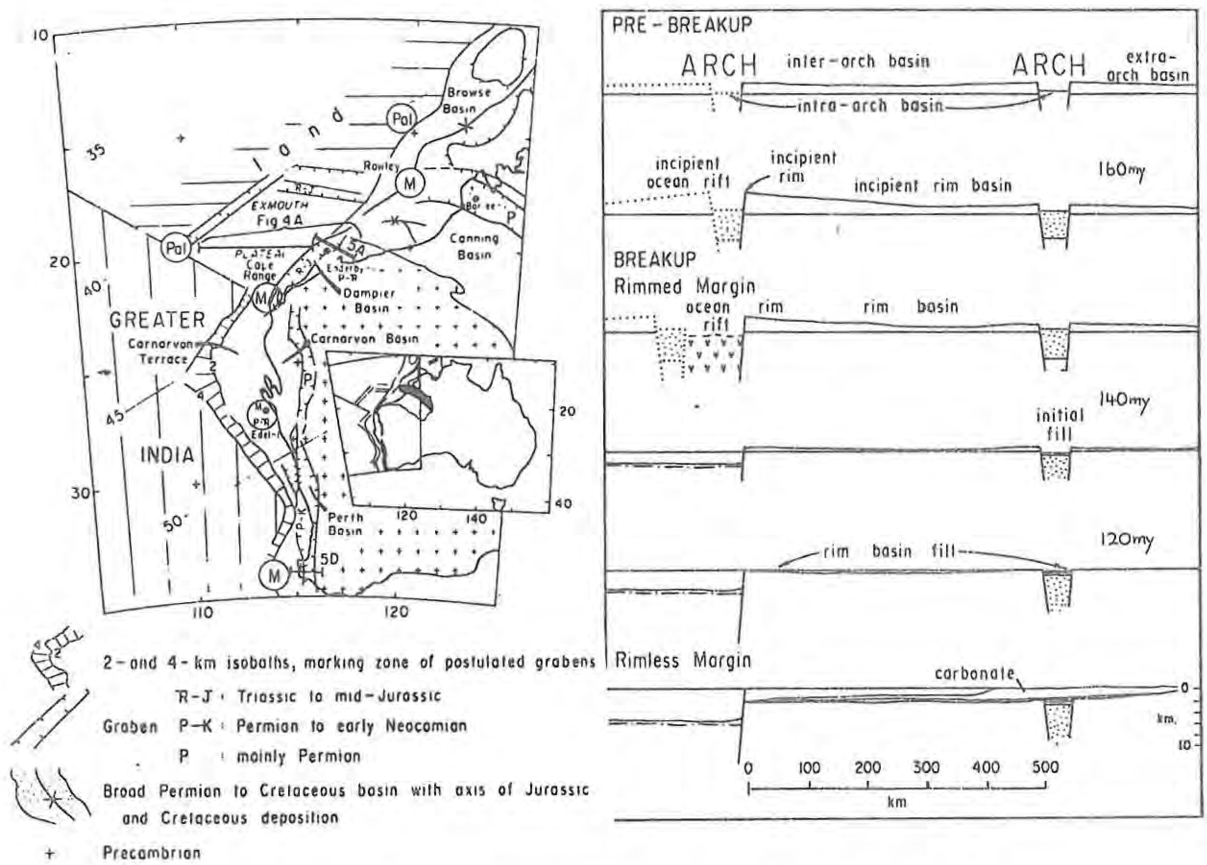


FIGURE 51 (A): Pre-breakup configuration of the western margin of Australia (Jurassic-Cretaceous) showing the Permian and Mesozoic grabens and basins. (B): Schematic sections showing the evolution of the multiple rifted arch system of the Exmouth Plateau and Damper Basin from pre-breakup grabens and inter-arch basin to sea-floor spreading stage and the development of a rim basin, follow d by subsidence and the progradation of a miogeosyncline wedge (from Veevers and Cotterill, 1976 and Veevers, 1977).

ocean basin is typically a number of kilometers below the mean surface level of the two adjacent continental fragments. The resulting sedimentation forms a characteristic sedimentary prism that spans the interface between continental crust and oceanic crust. The successive phases of deposition may form markedly diachronous facies along a rifted margin because most continental separations proceed as wedge-like openings rather than instantaneous separations along the whole length of the rift belt (Dickinson, 1974).

As the continental margin moves away from the mantle diapir beneath the mid-oceanic ridge, the originally uplifted margins of the initial rift would begin to subside. In conjunction, the continental margin is coupled to the oceanic lithosphere and will therefore tend to subside with it. The thermal contrast on each side of the offset margins would result in differential subsidence, with the transverse fractures acting as zones of decoupling between the continental blocks (Francheteau and Le Pichon, 1972). The resultant differential subsidence of parts of the continental margins would lead to the formation of shelf and coastal basins that are open towards the sea and which are approximately limited by the prolongation of the marginal offsets and corresponding fracture zones. Decoupling and differential subsidence along major hinge faults would initiate partial melting in the mantle diapir and would act as a conduit for magmatism. Typically a group of differentiated cauldera-type mafic to alkaline complexes would develop along these linears. In Angola, Brazil and South West Africa, groups of alkaline igneous complexes form distinct lineaments that can be correlated with transform faults that offset the Mid-Atlantic Ridge. The ages of the alkaline complexes are grouped between 135-125my and 80-50my and correlate with the initiation of continental separation and a later reactivation due to a change in the pole of rotation between Africa and South America (Marsh, 1973).

The Benue Trough is a 80-90km wide fault-bounded aulacogen that contains a sequence of gently folded Cretaceous sediments and volcanics. The Benue Trough is located on the Gulf of Guinea re-entrant on the west coast of Africa. The Benue Trough is bounded by two major faults that continue on the ocean floor as two major transform faults that offset the Mid-Atlantic Ridge. Alkaline, tholeiitic and andesitic volcanic activity was associated with the deposition of continental sandstones and playa lake sediments coeval with the initiation of rifting between Africa and South America. The initial graben stage of sedimentation and volcanism was followed by a major Albian transgression and the deposition of up to 2000m of shallow marine sediments that grade northwards into platform carbonates. The aulacogen was subjected to periods of tectonic reactivation with associated gentle folding of the sediments. Reactivation of the major boundary rifts led to the erosion and deposition of thick continental clastic wedges (Fig. 52). (Olade, 1975).

The Benue Trough underwent a similar evolution to most sedimentary basins on the continental margins of the Atlantic. The presence of anENE-WSW trending lineament, defined by a belt of charnockites, just to the north of the Benue Trough suggests that this aulacogen might be developed along an ancient lineament (McConnell, 1972). The Benue Trough is also bounded by two major faults that continue on the ocean floor as two major transform fault zones (Francheteau and Le Pichon, 1972). The Benue Trough-Atlantic continental margin junction has been frequently cited as a typical triple junction, genetically related to continental drift. However, this junction probably represents the trilate splitting of the continental crust by a mantle-derived thermal dome along ancient

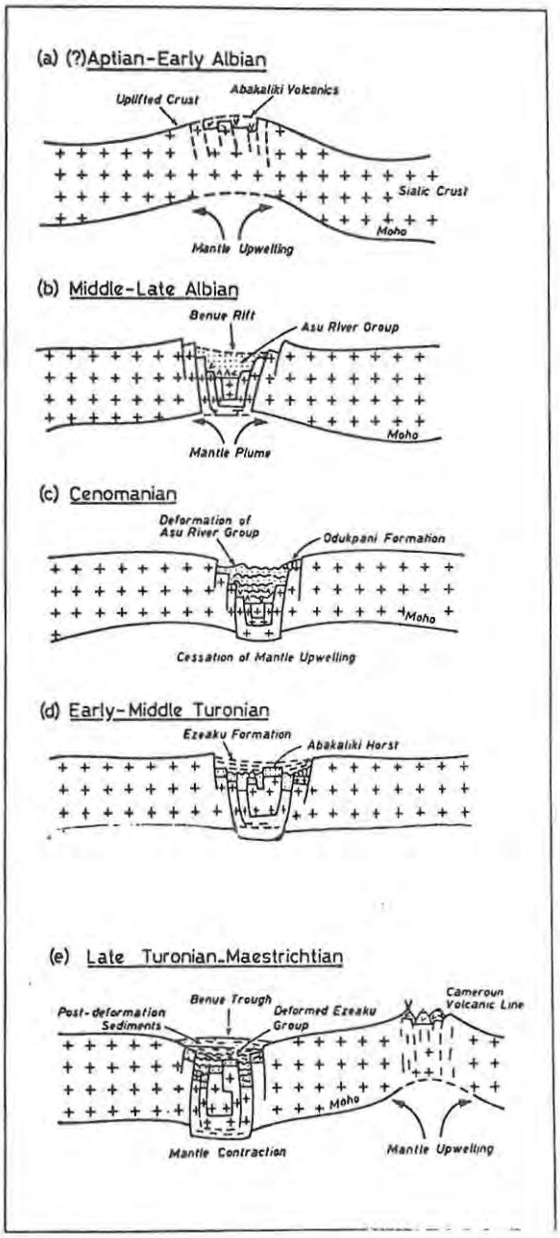


FIGURE 52: Schematic sections illustrating the tectonic evolution of the Benue Aulacogen (after Olade, 1975).

lineaments. Progressive horizontal extension caused two of the rifts to spread to form the South Atlantic. The stresses associated with the opening caused the Benue Trough to cease further extension so that it remained as a partially active aulacogen.

Along the South American and African continental margins, Late Jurassic and Early Cretaceous continental clastic sediments accumulated in half grabens unconformably above Palaeozoic sediments and crystalline basement. These early continental clastic sediments were succeeded by extensive Aptian evaporites which indicate the existance of a long narrow sea separating Africa and South America. Younger marine sediments record the continuing separation of the two continents. In most cases these deposits show a seaward thickening as a sedimentary wedge which is in marked contrast to the distribution of the older continental deposits in half grabens (Fig. 53) (Kent, 1977). The thick accumulations of strata on the margins of continental blocks correspond to the miogeosynclinal deposits of the Proterozoic and Palaeozoic as they are characterized by clear-cut contact relations with the continental basement and by a paucity of turbidites and interstratified volcanic rocks.

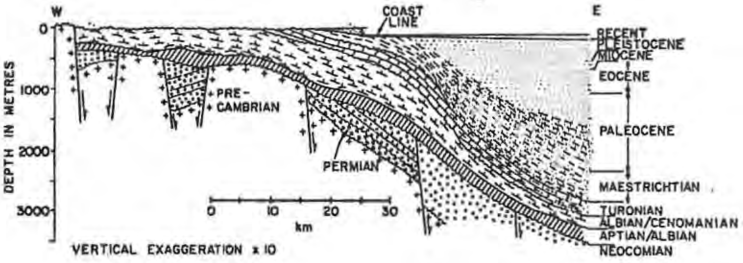


FIGURE 53: Section across the Sergipe-Algoas Basin on the Atlantic continental margin of Brazil showing the seaward thickening of a miogeoclinal sedimentary wedge in contrast to the confinement of pre-breakup Permian - Early Mesozoic sediments to rift-bounded proto-basins (from Kent, 1977).

The sediments on the North American Atlantic continental margins are preferentially developed in isolated fault-bounded troughs that are aligned approximately parallel to the continental slope (Fig. 54). The geometry of the basins can be explained by the clockwise rotation of the whole North American Continent in response to the differential opening of the Labrador Sea and the Atlantic Ocean (Sheridan, 1974). Up to 8-12km of Jurassic and younger shallow-water marine sediments accumulated in the block-faulted rifted continental margin, while Early Cretaceous and

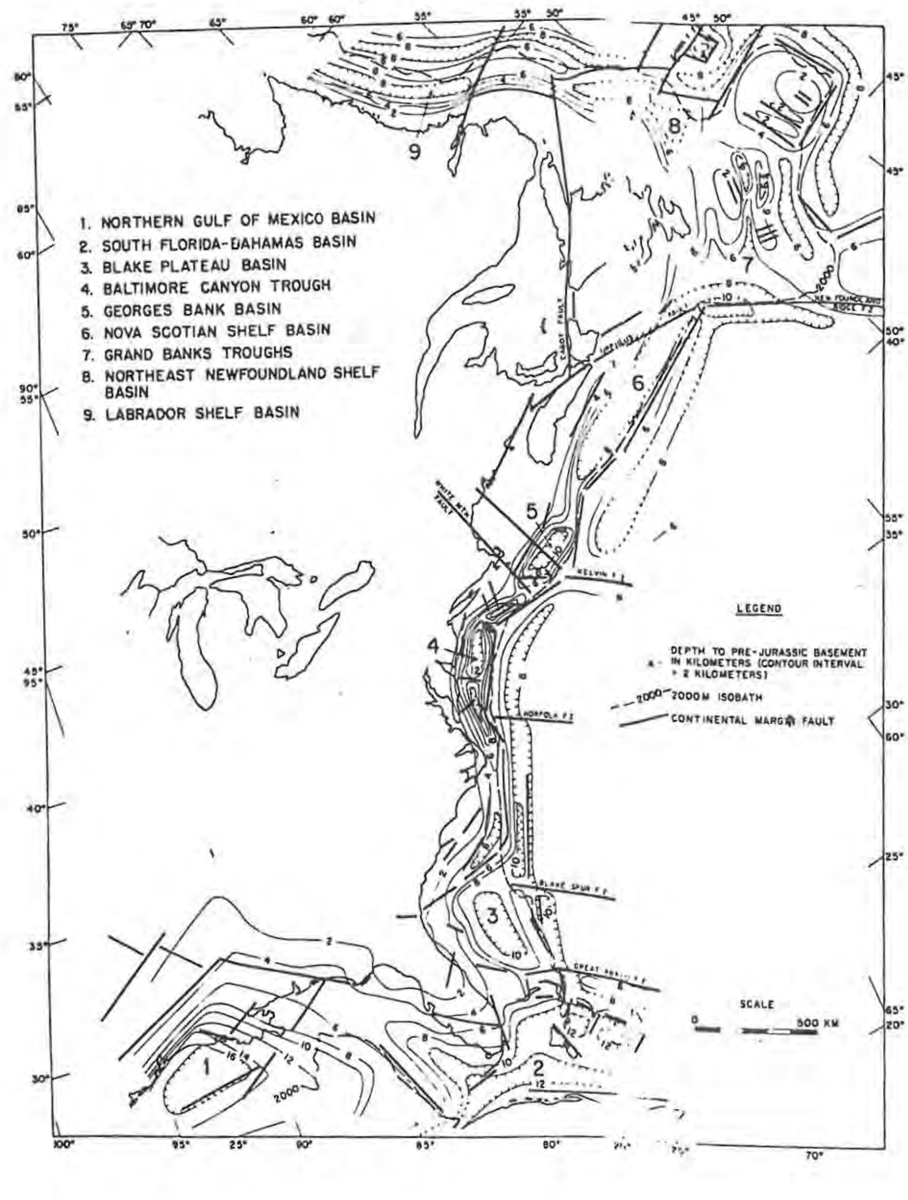


FIGURE 54 (A): Structural map of the Pre-Jurassic basement of the Atlantic continental margin of North America showing the development of narrow rift-bounded basins on the proto-continental margin and the decrease in the basement elevation away from the margin. (B): Conceptual reconstruction of the Atlantic continental margin illustrating the development of narrow rift-bounded basins by differential rotation during the opening of the Labrador Sea and the Atlantic Ocean (from Sheridan, 1974).

Jurassic carbonate and evaporite deposits are preserved in the deeper basins off-shore. Subsequent subsidence of the rifted Atlantic continental margin associated with the westward drift of North America during formation of the Mesozoic and Cainozoic Atlantic Ocean also allowed room for the deposition of considerable thicknesses of Mesozoic and Cainozoic geosynclinal sediments (Sheridan, 1974).

A global synchronization of certain transgressions and regressions have been recognized as well as apparent global synchronization of short intra-Cretaceous periods of rapid subsidence. The penecontemporaneous Aptian-Albian phase of rapid cratonic sedimentation in North America and Russia, and the wide-spread marine transgression and rapid sedimentation in Brazil and on the North American Atlantic continental margin all suggest that the controlling strain was caused by a common global geodynamic process (Whitten, 1976).

Subduction and Island Arcs

In the global system of rigid lithospheric plates, subduction is a logical consequence of plate accretion at a mid-oceanic ridge. Geodectic levelling after major historical earthquakes in both Japan and Alaska indicated that the earthquakes resulted from the sudden ocean-ward relaxation of potential energy which caused the sudden movemen s of huge glide masses moving over a spoon-shaped base (Fig. 55). These relaxations of potential gravitational energy caused subsidence on the continents and upthrusts along the side of the adjacent subduction trench. This suggests that subduction is the response to the gradual thrusting of the continental plate over the oceanic plate (Fig. 56). (Van Bremmelen, 1976). In this way subduction is due to the movement of both the continental and oceanic plates in response to horizontal extension related to the generation of new oceanic crust along the mid-oceanic ridge.

Volcanically active island arc systems characteristically develop in response to subduction. Island arcs show a similar evolution to intracratonic rift systems and are characterized by graben formation (Fig. 56) and profuse, mainly calc-alkaline volcanism with some alkaline and tholeiitic magmatism. Typically the basaltic volcanism changes from tholeiitic to high-alumina basalt and then to olivine alkali basalt away from the volcanic front, in response to the increase in depth of the subduction zone within the mantle. This would suggest that shearing and

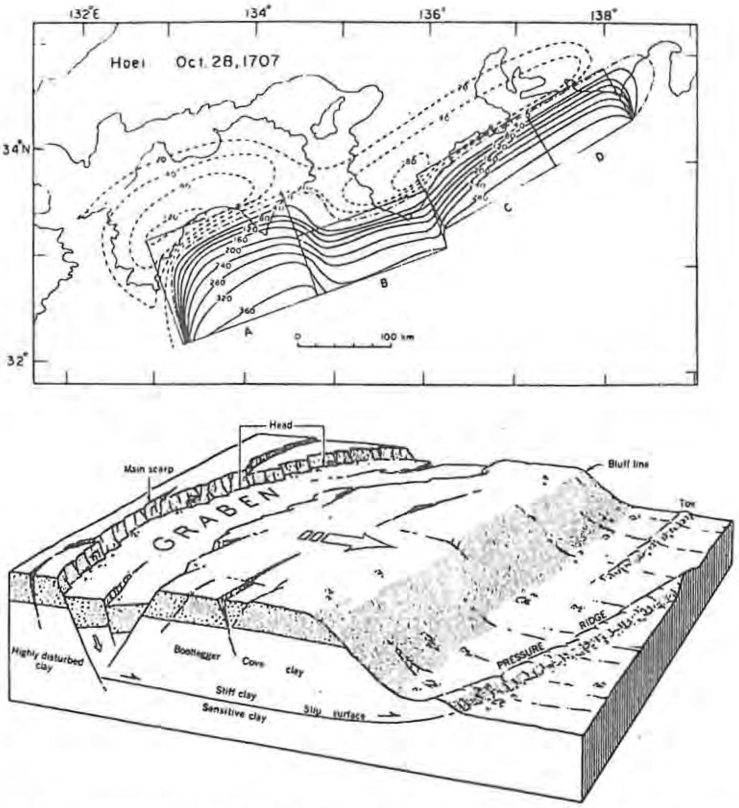


FIGURE 55 (A): Geodectic data on the Hoei Earthquake in the western part of the Japan Arc illustrating the rise of the ground level on the trench side and subsidence on the continental block. (B): Block diagram illustrating the translatory slide towards the trench generated by a major earthquake in Alaska, 1964, which has a similar geodetical response as that of the Hoei Earthquake in (A) (from Van Bremmelen, 1976 and Spencer, 1972).

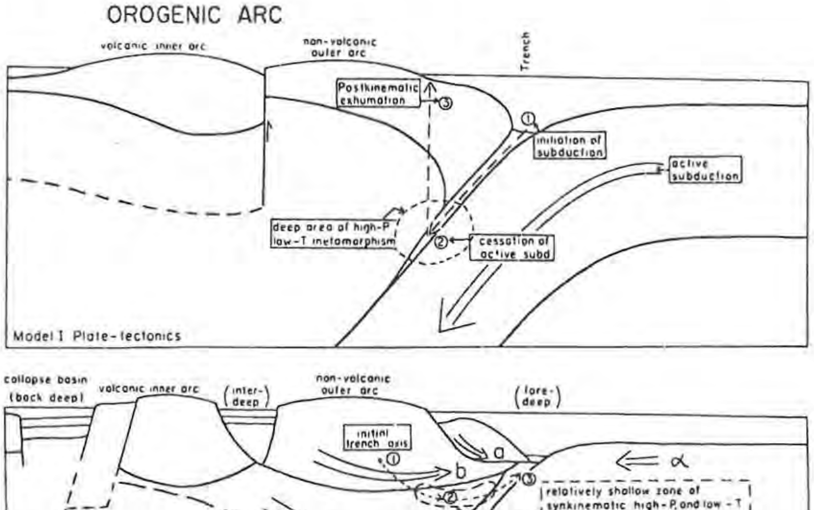


FIGURE 56: Origin of the Japan Arc. (A): According to the concept of active subduction by the thrusting of the oceanic plate beneath the continent. (B): Due to the interaction of an oceanic plate moving away from an active mid-oceanic ridge and thrusting of the continental plate over the oceanic plate in response to horizontal extension associated with secondary mantle diapirism below the active volcanic arc. Note that the geometry of the low-angle thrusts correspond to the geodectic data derived from major earthquakes in active island arcs (Fig. 55) (from Van Bremmelen, 1976).

the generation of frictional heat is sufficient to cause partial melting of the mantle adjacent to the descending ocean plate. Volcanism and plutonic activity in the Andes shows a remarkable association with the spreading rate, suggesting that the rate of subduction and magma generation are related (Fig. 57) (Pitcher, 1979). The incorporation of a rigid cool lithospheric plate into the upper mantle would be expected to generate secondary effects. It is possible that frictional heat associated with shearing on the upper margins of the plate would cause partial melting of the mantle rather than in the relatively cool descending oceanic plate. Partial melting of the mantle would lead either to the development of a density difference and the segregation and rise of mantle diapirs, or to the rise of the melting isotherm above the low velocity zone, which would in effect be identical in nature to a mantle diapir.

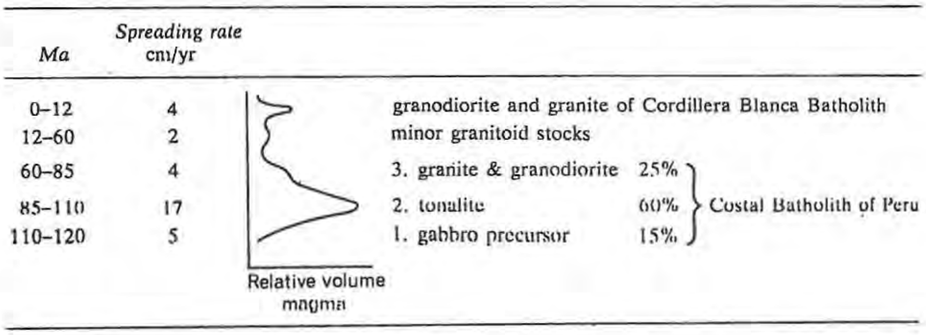


FIGURE 57: The relationship between the volume of magma produced during the formation of the Coastal Batholith of Peru and the spreading rate of oceanic plates in response to eastward subduction below South America (from Pitcher, 1978).

However, since mantle advection is the more general process of heat transfer, it is likely that a secondary mantle diapir would begin to rise after a critical amount of low density partial melt had accumulated along the subducting plate. In view of the relationship between magmatism and sea-floor spreading rates, it would seem that at slow spreading rates isolated mantle diapirs, or magma diapirs, would rise from the Benioff Zone. Volcanic activity at surface would then be marked by a distinct petrographic zonation behind the volcanic front that is well illustrated by the Quaternary Volcanoes in Japan (Fig. 58) (Carmicheal, et al, 1974). At high sea-floor spreading rates the generation of large amounts of basaltic partial melt in the mantle might be sufficient to form a secondary mantle diapir. This would rise in a similar fashion to a primary mantle diapir and would interact with the continental crust in an

FIGURE 58: Distribution of tholeiite (small circles), high-alumina basalt (open circles) and alkali olivine basalt (solid circles) in Quaternary volcanoes in Japan. The zonation parallels the volcanic front developed above the subduction zone (Carmicheal, et al, 1974).

identical way. The interaction of associated basaltic magma diapirs with the continental crust would generate calc-alkaline magmas. In view of the tectonic setting, the behind-trench zones would be subjected to compressive stresses. As a result the rise of magma diapirs would be confined and calc-alkaline volcanism would predominate over alkali basalt and tholeiitic volcanism. Progressive horizontal extension associated with the spreading mantle diapir would eventually result in profuse tholeiitic volcanism, dyking and the generation of a marginal sea behind the arc. Horizontal extension associated with a mantle diapir behind the trench would also promote thrusting of the island arc system over the descending oceanic plate.

As islands arc systems evolve, a series of back-arc marginal basins would be generated by crustal extension behind the frontal arc and would produce oceanic crust similar to normal ocean basins. The western margin of the Pacific Ocean is characterized by a number of marginal ocean basins that illustrate the progressive migration of the subduction zones to the east, away from the continents (Fig. 59) (Karig and Moore, 1975). Oceanic

FIGURE 59: The distribution of trenches and marginal basins in the Western Pacific Ocean showing a three-fold classification of the marginal basins based on increasing age, depth and crustal heat flow (from Karig and Moore, 1974).

crust associated with mid-oceanic ridges is characterized by a well defined magnetic pattern due to periodic reversals of the geomagnetic field. The ocean floor associated with marginal ocean basins is, however, characterized by a diffuse magnetic pattern. This is probably a manifestation of the mechanisms involved in plate accretion. Mid-oceanic ridges are associated with a discrete mantle diapir while a number of smaller discontinuous mantle diapirs might be associated with the generation of a subduction zone. As a result, horizontal extension in marginal basins might be a more random process than that in the narrow active zones in mid-oceanic ridges. The collapse of marginal basins and subsequent metamorphism and orogeny could be related to a change in the rate or direction of subduction, or more likely, related to the collapse of the mantle diapir during inactive subduction periods.

Marginal basins are characterized by the development of asymmetric sedimentary patterns in contrast to the symmetric patterns developed on aseismic continental margins that rim large ocean basins. Sedimentation is characterized by the thick accumulation of volcaniclastic debris on large submarine fan complexes adjacent to the volcanic arc (Karig and Moore, 1975). These thick volcaniclastic turbidite sequences and pelagic clay deposits are charactered by a paucity of continentally derived sediments and are identical in nature to the thick greywacke sequences found within the Archean Greenstone Belts.

MANTLE ADVECTION AND CRUSTAL EVOLUTION

Throughout geological history there has been a close relationship between volcanic activity, basin development and subsequent orogeny, metamorphism and plutonic activity that this sequence of events cannot be the chance superposition of unrelated events, but must be related to a common geodynamic process. In the present plate tectonic cycle there is evidence of coupling between mantle processes and surface responses. This is also illustrated by a direct relationship between periods of high geomagnetic reversal frequency related to the core, and regression in response to uplift of the continental crust (Fig. 60), suggesting that high geomagnetic reversal frequencies correspond to periods of intensified mantle advection.

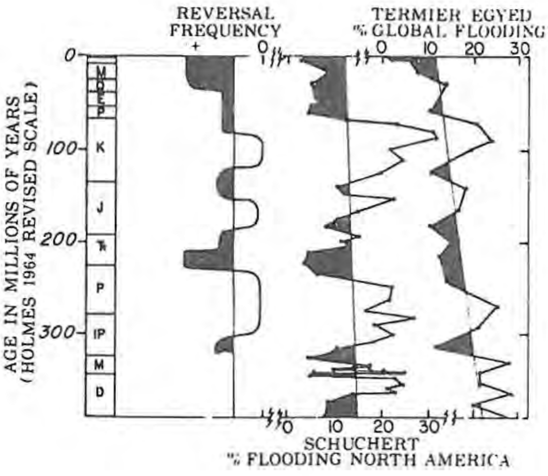


FIGURE 60: Approximate geomagnetic reversal frequency history for the last 300 my (left) compared to sea level (% flooding) changes for North America, and the entire globe (right). Note approximate correspondence between low sea level (regression) and high geomagnetic reversal frequency (from Vogt, 1965).

The major control on mantle processes with time has been the transfer of thermal energy from the mantle to the crust. The almost complete confinement of komatiitic magmas to the Archean suggests that the Archean was characterized by increased partial melting of mantle peridotite in response to the presence of excess heat within the mantle. This excess heat initiated extensive mantle diapirism, so that the relatively thin sialic crust was inundated by extensive rifting and arc-type volcanism in the Archean. The boundary between the Archean and the Proterozoic represents a major evolutionary stage in the history of the earth, and is probably related to a marked decrease in the heat generated in the mantle, mainly by the radioactive decay of U^{235} and K^{40} (Fig. 61) (Salop and Scheinmann, 1969). Estimates of the fall-off in the production of thermal energy by radioactive decay vary, but starting from 4500 my ago it seems reasonable that by 3000my the heat production might have decayed to half its original value and that by 1000my to a value less than twice the present (Fyfe, 1976). The geothermal gradient in the crust would have a direct association with the steady-production of thermal energy in the mantle. A gradual decrease in geothermal gradient with time can explain the predominance of greenschists to the low-grade metamorphic terrains of the Archean and the gradual appearance of early "blueschists" in the Palaeozoic and the predominance of typical blueschists and zeolite facies rocks to the low-grade metamorphic terrains of the Mesozoic. However, the marked increase in high-pressure low-temperature assemblages at the beginning of the Mesozoic must be primarily due to the initiation of subduction as a wide-spread crustal response to mantle advection.

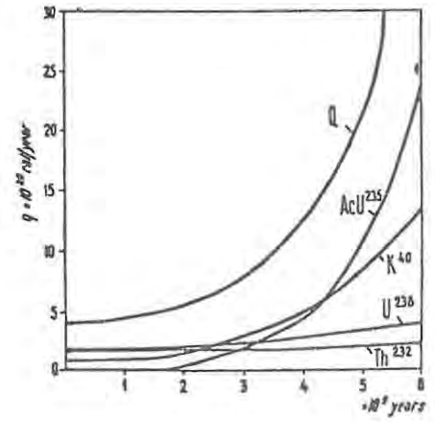
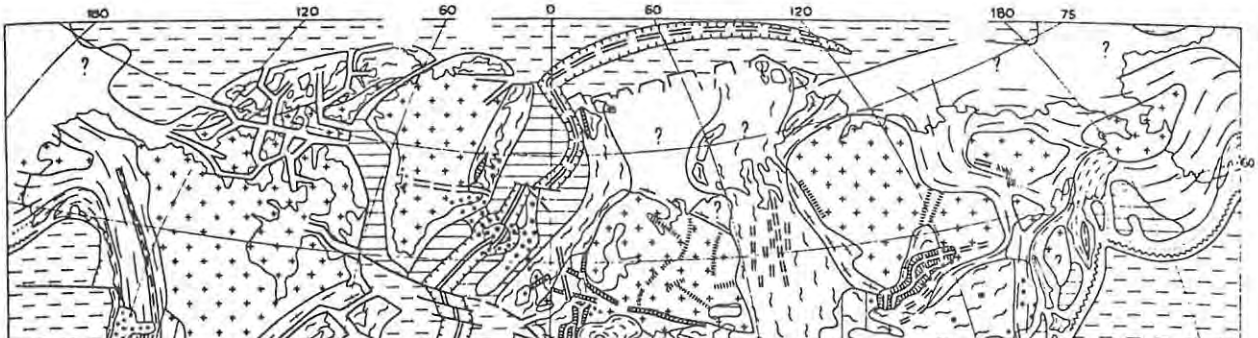


FIGURE 61: The change in thermal energy generated by the radioactive decay of U^{235}, U^{238}, U^{40} and Th^{232} disseminated within the mantle and crust of the earth with time (from Salop and Scheinmann, 1969).

Global processes have definitely evolved through time, from the relatively simple Archean active-arc system, through the bimodal miogeosyncline-eugeosyncline system of the Proterozoic to the Mesozoic to Recent complex plate-tectonic system involving the sequential interaction of accreting and subducting lithospheric plates (Fig. 62). There has been an increasing degree of differentiation of volcanic and sedimentary facies relationship with time. The often remarked similarity between Mesozoic island arc systems and Archean greenstone belts has been used to project plate-tectonics back to the Archean. However, the close similarity is due to secondary mantle advection in response to continued subduction, which is in all respects identical, although on a much smaller scale,to extensive primary mantle advection in the Archean. The basement highs that separated miogeosynclines and eugeosynclines in the Proterozoic probably have a similar tectonic origin as rim basins on the margins of the continental shelves of the Mesozoic and Cainozoic. The generation of isolated horst blocks during the initial stages of rifting and yoked-basin development (Fig. 63), probably would remain as tectonic highs during further horizontal extension. The generation of these horst blocks and the site of continued horizontal extension and basin development is probably a random process so that some geosynclines and continental margins are characterized by tectonic basement highs, while others are not. The more extreme horizontal extension in the Mesozoic has resulted in a more rapid transition between shelf and basinal sediments than in the geosynclines of the Proterozoic (Fig. 64).

Another major evolutionary change is that basin development and subsequent orogeny became progressively separated through time. Metamorphism, plutonic activity and the collapse of the Archean active arc systems followed closely on basin development. As a result, Archean orogeny is characterized by relatively plastic deformation in response to reactivation of ductile basement and a high proportion of semi-crystalline granitoids in the sialic crust. The Archean was characterized by a definite lack of differentiation of tectonic style, probably as a result of very local source of orogenesis. The Proterozoic is, however, marked by a characteristic differentiation in tectonic style which is indicated by the contrasting structural styles of miogeosynclines and eugeosynclines. The rapid development and subsequent collapse of eugeosynclines causes high-grade metamorphism and intense structural deformation in contrast to the gentle folding



Recent (late cenozoic) rift belts and zones. Continental rift belts: 1 = epiplatform arch-volcanic rift zones; 2 = epiplatform crevice-like rift zones; 3 = epiorogenic rift zones and belts; 4 = intercontinental rift zones. Oceanic rift belts: 5 = mid-oceanic ridges with axial rift valleys; 6 = mid-oceanic ridges without clearly expressed rift valleys; 7 = areas of mid-oceanic ridges with important volcanic manifestations; 8 = some large-scale faults and wrench faults active during the Cenozoic.

Pre-late Cenozoic zones of extension, fracturing of the crust and graben building – probable ancient analogues of recent rift zones (continental and intercontinental):

9 = Late Mesozoic and Early Cenozoic; 10 = Early Mesozoic; 11 = Paleozoic; 12 = Late Proterozoic; 13 = areas of Late Cenozoic volcanism (outside of alpine geosyncline orogenic belts); 14 = zones of Cenozoic epiplatform orogenesis (mountain building); 15 = recent deep sea troughs; 16 = recent geosynclinal zones; 17 = zones of Alpine and Laramide folding; 18 = zones of Mesozoic folding (Kimmerides, Nevadides etc.); 19 = zones of Paleozoic folding (Hercynides, Caledonides); 20 = zones of late-Proterozoic folding or regeneration (Grenvillides, Bailalides etc); 21 = Pre-late Proterozoic platforms; 22 = areas of the oceanic floor with sub-continental crust; 23 = deep sea depressions with sub-oceanic crust; 24 = oceanic basins with crust of oceanic type.

FIGURE 62: The tectonic pattern of the globe illustrating the distribution and progressive disruption of older sialic crust by orogenic belts of different ages which has culminated in the present lithospheric plate system (from Milanovsky, 1972).

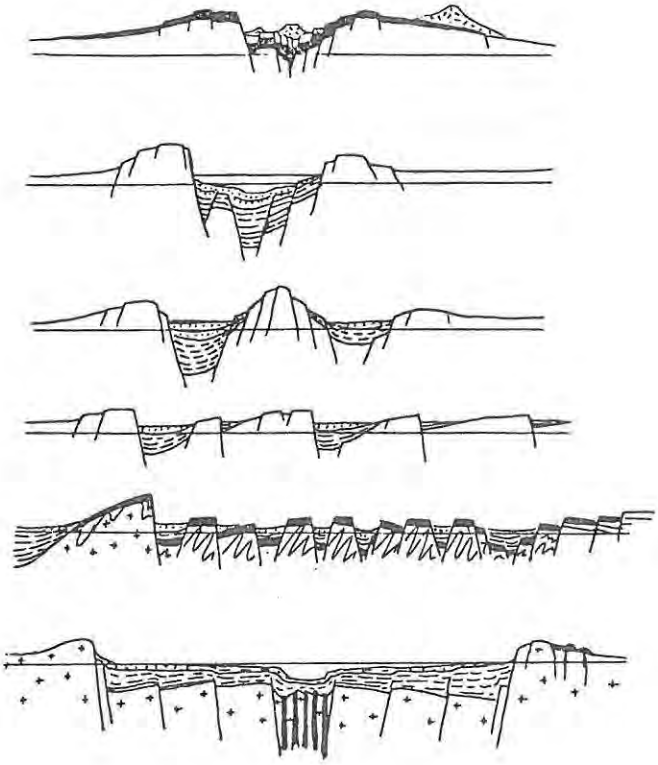


FIGURE 63: A sequences of the typical structural types of rift zones illustrating the effect of progressive horizontal extension on the development of rifted basins (from Milanovsky, 1972).

and low-grade metamorphism in the miogeosynclines. Collapse of the eugeosynclines reactivates the separating basement high as a tectonic borderland which results in the shedding of flysch and mollase-type sediments on the earlier sediments of the miogeosyncline. In the Mesozoic and Cainozoic basin development and orogeny are often divorced in time and space and are no longer related to the rise and subsequent collapse of a mantle diapir. The change in tectonic style is related to the episodic but progressive increase in horizontal extension through time in response to an increase in the ridgidity of the sialic crust. During the early history of the earth lower crustal processes were probably dominated by ductile flow but as the thermal energy has decayed with time lower crustal processes have become dominated by brittle deformation. Basin development right through time has been dominated by subsidence in response to horizontal extension associated with a spreading mantle diapir. In the early history of the earth it would appear that the sialic crust and early lithosphere were ductile and remained coherent, while in the later stages of evolution, the crust was unable to remain as one coherent mass and so has initiated dyke intrusion and progressive sea-floor spreading. The first concerted

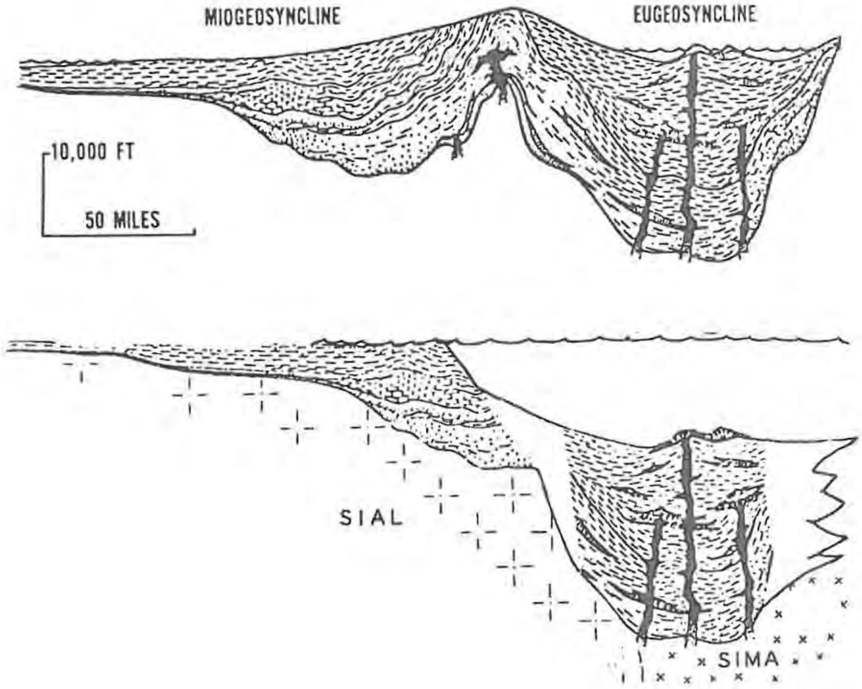


FIGURE 64: The relationship between an ensialic mio-eugeosynclinal couplet and a ensialic-ensimatic geosyncline that corresponds to a modern continental margin-ocean basin (from Dietz and Holden, 1974).

effort of extreme horizontal extension appears to have started in the Mid Proterozoic,illustrated by the development of quasi-continental crust in the Keweenawan Rift System in North America. However, it was only in the Palaeozoic that continental separation reached the stage of the generation of oceanic crust that was later obducted during orogeny to form ophiolite complexes. In the Palaeozoic horizontal extension only reached this stage near the closing stages of the spreading of the mantle diapir so that orogenic collapse followed closely on this incipient sea-floor spreading. However, in the Mesozoic continental rifting and sea-floor spreading developed rapidly in response to horizontal extension in a relatively brittle crust during the early stages of mantle diapirism. As a result orogeny is no longer associated with the original mantle diapir but rather with secondary diapirism above a subduction zone.

Although the intensity of magmatism associated with mantle diapirism has decreased with time, the intensity and continuity of rifting has increased. During the extensive period of intra-cratonic rifting in the Mid Proterozoic rifting and basin development appears to have been isolated in widely separated parts of the cratons (Fig. 23). However, by the Late Palaeozoic continuous rift-bounded grabens developed in response to intense mantle diapiric activity that eventually led to sea-floor spreading and the breakup of Gondwanaland and Laurasia (Fig. 65).

FIGURE 65: Schematic pattern of the Mesozoic rift system in the Northern hemisphere (from Ramberg and Newman, 1978).

The change in rifting patterns with time is probably due to the change in the mantle advective pattern from the early system dominated by first degree harmonics to the present system with dominant fifth degree harmonics.

A change in the intensity and geometry of mantle advection systems with time can explain the non-uniformitarian behaviour of the geological evolution of the earth. A model of mantle advection therefore only involves the initiation of crustal uplifts, rifting, volcanism and basin development and the subsequent collapse of the basin, orogeny, metamorphism and plutonic activity (Fig. 66). The evolution of the earth involves the interaction of mantle diapirism with a progressive change in mantle thermal energy and a progressive thickening and rigidity of the crust with time (Fig. 67).

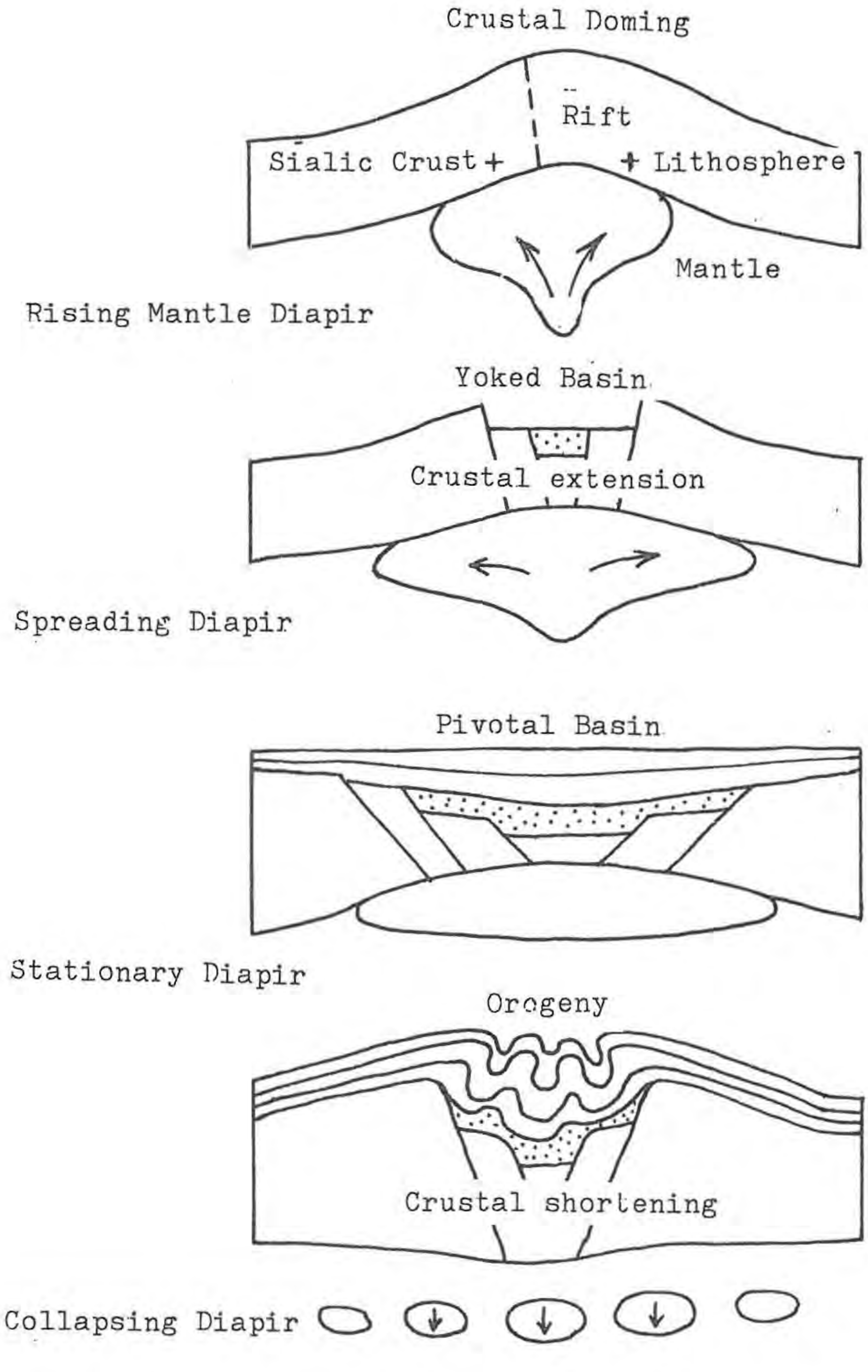


FIGURE 66: A Model of Mantle Advection, Rifting and Basin Development.

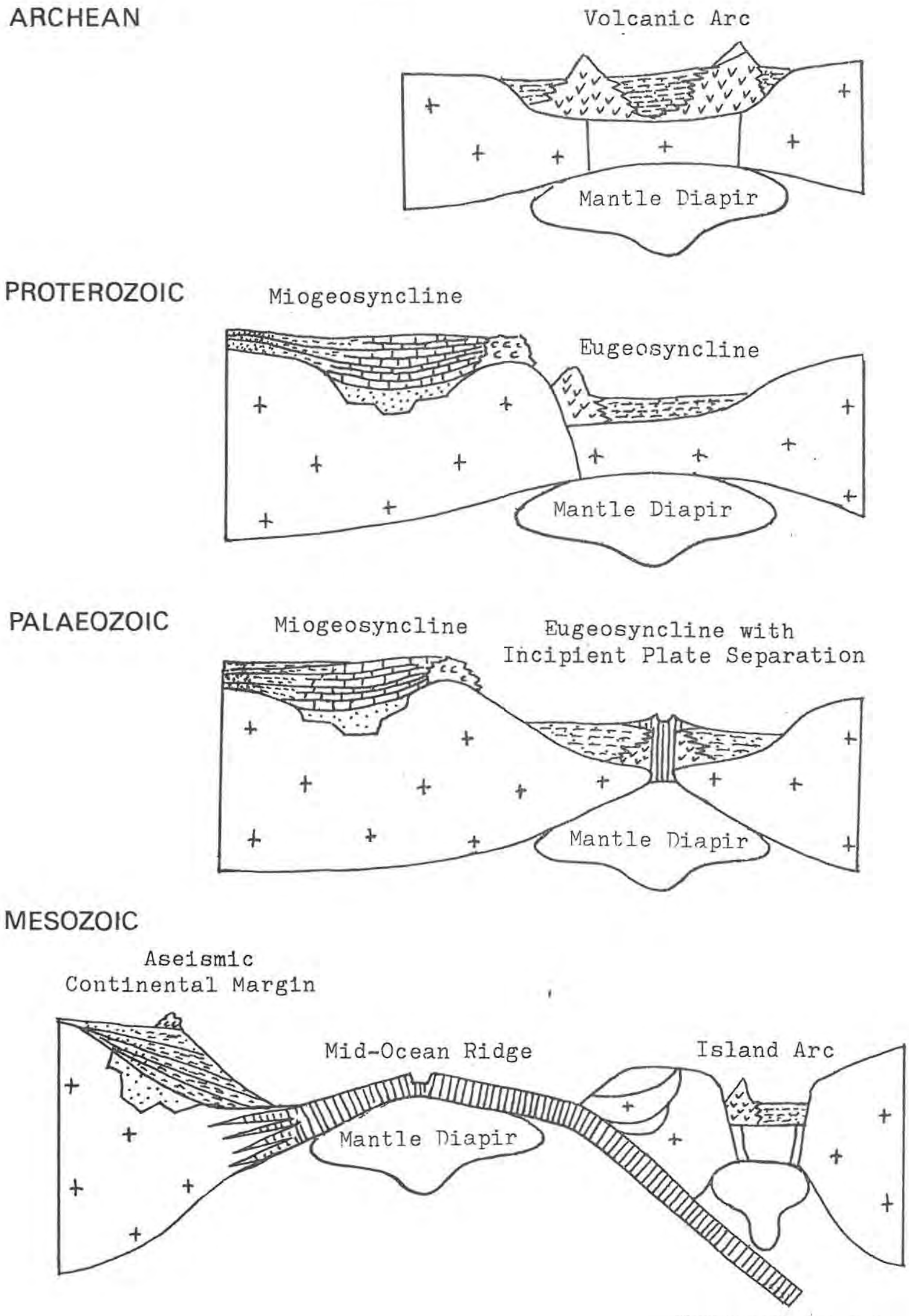


FIGURE 67: The Evolution of Rifting through Time.

RIFTS AND STRATIFORM AND STRATABOUND ORE DEPOSITS

Rifts are penetrative taphrogenic faults in the earths crust which act as major conduits for the transfer of magmas, from the mantle and lower crustal levels to the surface. Archean komatiite-hosted nickel deposits are developed adjacent to major rifts which acted as conduits for the transfer of sulphur-rich ultramafic magmas from the mantle.

Rifts tend to control basin development, volcanism and sedimentary facies distribution. Rifts control the development of geosynclines as well as the timing and distribution of the associated volcanism. The rifts tend to act as permeable zones for the migration of both magmas and late-stage magmatic metalliferous brines, so that major volcanic arcs and associated volcanogenic ore deposits are concentrated along the boundary rifts of geosynclines and back-arc basins. Rifts control the development and facies distributions of sediments within aulacogens and the adjacent platforms. These taphrongenic faults also act as permeable zones for the transfer of relatively low temperature magmatic brines from differentiated plutonic complexes at depth. The exhalation of these metalliferous brines into reducing environments leads to the development of volcano-sedimentary deposits. The permeability of the rifts controls the extent of volcanic activity so that there is a complete range in ore deposts from volcanogenic deposits to sediment hosted strataform ore deposits. The timing between deposition and metalliferous brine activity is important in determining the relationship between the ore deposits and the host-strata stratiform volcanogenic and volcano-sedimentary deposits formed syn depositionally and therefore show well defined relationships between the ore and host strata. In relatively inactive yoked-basins and platforms, it appears that hydrothermal activity post-dates sedimentation so that some carbonate lead-zinc deposits, stratiform copper deposits and some uranium deposits are post-depositional and show cross-cutting relationships and replacement textures. In these post-depositional deposits the conditioning of the sediments during deposition is critical in controlling the localization of these stratabound ore deposits.

Stratiform and stratabound ore deposits have an intimate relationship with rifts, even though the timing of volcanism, sedimentation and metalliferous brine activity vary between deposit types and from deposit to deposit. The close association of rifts and stratiform and stratabound ore deposits will be illustrated by examining the relationships in a number of the worlds' major ore deposits.

ARCHEAN NICKEL DEPOSITS

Kambalda-type nickel deposits are directly associated with Archean ultramafic magmatic activity adjacent to major taphrogenic rifts. Nickel sulphide mineralization in the Thompson Belt, Canada is directly associated with ultramafic magmatism along a major taphrogenic rift that marks the boundary between the Superior and Churchill structural provinces (Fig. 68). In Australia nickel mineralization is confined to the Norseman-Wiluna Belt in the Yilgarn Block (Fig. 14). The Norseman-Wiluna Belt is comprised of a series of elongate greenstone belts and areas of granite within a major north to north-north-westerly trending braided fault zone. These taphrogenic faults, or rifts,

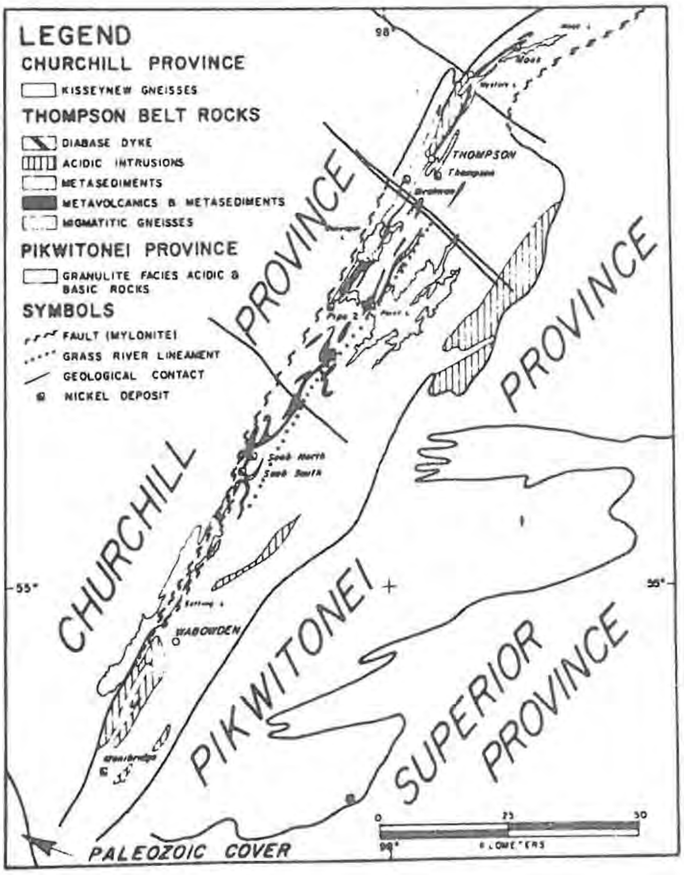


FIGURE 68: The regional setting of the Thompson Belt, Canada, illustrating the development of komatiite-hosted nickel deposits along the rift that separates two major structural provinces (from Peredery, 1979).

controlled magmatic activity, thermal metamorphism, deformation and granite intrusion within the greenstone belts (Binns, et al, 1975). The nickle sulphide mineralization is hosted by ultramafic komatiitic flows, differentiated sills and dykes in close proximity to the major rifts.

The Kambalda nickel deposits in the Norseman-Wiluna Belt are developed in the basal komatiitic flows around the Kambalda Dome. The Kambalda Dome is confined between two major regional faults, and is significantly intruded by a late-stage intermediate to felsic pluton which indicates that the Kambalda Dome is situated within a zone of intensified magmatic activity. The komatiitic volcanic flows tend to thicken within some of the major fault-bounded grabens within the Kambalda Dome area, indicating that faulting occured during the volcanic activity (Ross and Hopkins, 1975).

The Kambalda nickel deposits are characteristically developed in the basal contact of the komatiite flows. About eighty percent of the main massive sulphide ore deposits are associated with the basal flow of a sequence of komatiitic ultramafic lavas, while minor amounts of disseminated sulphides are found at the base of some of the higher komatiite flows. The high-grade ore shoots, particularly the Lunnon Shoot, are controlled by small fault-controlled grabens that trend parallel to the bounding faults (Fig. 69).

Although ultramafic volcanics have been documented from the Palaeozoic in North America, komatiitic volcanics are almost exclusively restricted to the Archean. Komatiitic magmas are characterized by higher magnesium and nickel contents, and are therefore more extensive partial melts of the mantle than tholeiitic magmas. Komatiitic magmas commonly form the basal parts of major domical ultramafic to felsic volcanic piles. These initial komatiitic magmas are due to extensive partial melting under the high Archean geothermal gradients during the initial rise of a mantle diapir. It seems that the Archean mantle was enriched with respect to sulphur, as more recent extensive or limited partial melts of the mantle are notably sulphur deficient (Naldrett and Cabri, 1976).

The rate of extrusion of a komatiitic magma would have to be sufficient to counter gravity settling of the immiscible sulphide phase. A sulphide drop would have a settling velocity about thirty three times that of an equivalent sized olivine crystal (Naldrett and Cabri, 1976). Therefore

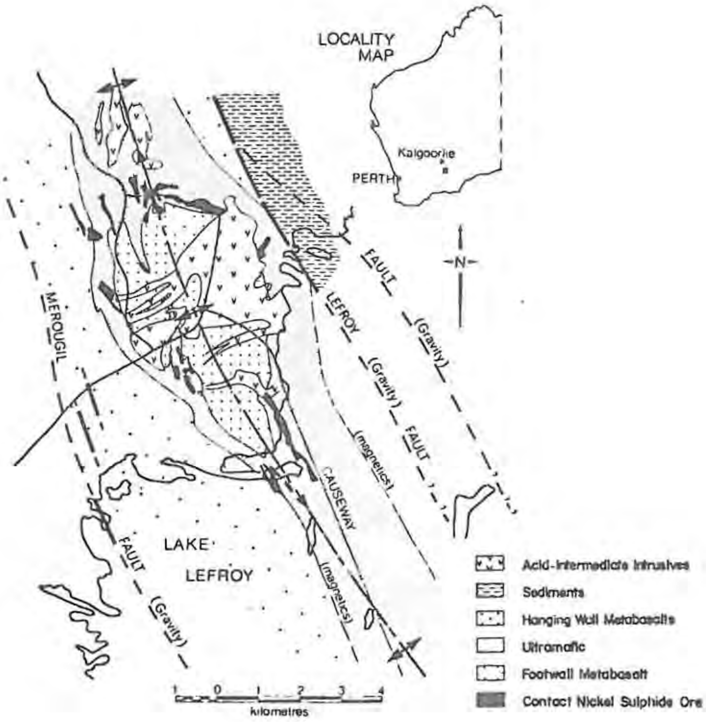


FIGURE 69: The distribution of komatiite-hosted nickel sulphide mineralization around the Kambalda Dome showing the trend of major ore shoots parallel to the major faults (from Ross and Hopkins, 1975).

the main reason why komatiite-hosted nickel deposits are associated with major rifts is because these taphrogenic faults acted as permeable conduits for the rapid extrusion of sulphide-rich ultramafic magmas from the mantle. If the ultramafic magmas rose at a reduced rate the heavier sulphide phase would have segregated during ascent. This is probably the reason why layered ultramafic complexes, which crystallized under relatively stable conditions, are not mineralized and why differentiated ultramafic sills adjacent to the rifts contain disseminated nickel sulphides.

EUGEOSYNCLINAL VOLCANOGENIC ORE DEPOSITS

Major taphrogenic rifts are permeable channels for magmatic activity. Volcanic centres would preferentially build up at the intersections of transverse faults with the main rifts. When the passage of the mantle-derived magma through the crust is unobstructed, the extrusion of undifferentiated and unfractionated magmas would lead to the build-up of extensive tholeiitic strato volcanoes, consisting of either sub-aerial amygdaloidal flows or submarine pillow lava sequences. When tholeiitic magmas are confined to lower or upper crustal cauldera-type magma chambers magmatic differentiation would lead to the formation of differentiated sills and the production of siliceous magmas which could be extruded at surface as rhyolites, part of the bimodal basalt-rhyolite volcanic suite. Such tectonic conditions are likely to exist beneath relatively thick sedimentary piles or thick sialic crust. It would only be during periodic movements that conduits would open to allow the transfer of magma to surface. Some large differentiated gabbroic sills possibly represent near surface magma chambers.

Calc-alkaline magmas are generated by the retardation of tholeiitic and alkaline magma diapirs in response to interaction with the sialic crust (Burnham, 1979). Should these diapirs be sufficiently retarded, particularly by ductile lower crust and sediments subjected to regional metamorphism, they would remain at low crustal depths to form differentiated granitiod plutons (Pitcher, 1979). If, however, in the early stage of the orogenic cycle these magma diapirs move up along major rifts through relatively brittle sialic crust, they would be extruded as calc-alkaline volcanics. As they have been retarded they typically post-date the early extensive mafic volcanism. Should the relatively thick sialic crust remain in a state of stress, it is possible that only calc-alkaline magmas would reach the surface. Calc-alkaline magmas have significant water contents and as a result are characterized at surface, by explosive volcanism with the formation of thick andesitic to dacitic pyroclastic and tuffaceous units. The viscosity of highly differentiated rhyolitic calc-alkaline magmas is generally so high that they commonly form diapiric lava domes.

In the upper crustal levels large calc-alkaline diapirs would initiate cauldera subsidence and the development of rift-bounded volcanic depressions. The progressive differentiation of the calc-alkaline magmas under relatively stable conditions would lead to inward crystallization and the concentration of the incompatible elements into the rest liquid. In a tectonically active region fractional crystallization is likely to be disturbed, which would lead to periods of relatively rapid crystallization and poor liquid-crystal separation. Periodic reactivation of marginal faults would lead to the expulsion of magma from the cauldera-type reservoir and further pressure quenching. As a result, the build-up of the incompatible elements would be slower and towards the end stages of crystallization it is probably unlikely that the magma would become saturated with water. However, during a tectonically inactive period slow fractional crystallization and good crystal-liquid separation would lead to the build-up of water and the other incompatible elements until such a stage that a metalliferous hydrous phase would develop (Fig. 70). The vapour phase would be associated with the most differentiated rhyolite magma, usually towards the end of a particular mafic to felsic volcanic cycle. Similarly the progressive fractional crystallization of the tholeiitic magmas under tectonically quiesent periods would lead to the build-up of the incompatible elements and water to form a magmatic hydrous phase. The chemistry of the magma would determine the metal association in the metalliferous brines; Cu-Pb-Zn-Sa-Ag-rich brines are associated with calc-alkaline magmas, while Cu-Zn-Au-rich brines would be associated with tholeiitic magmas.

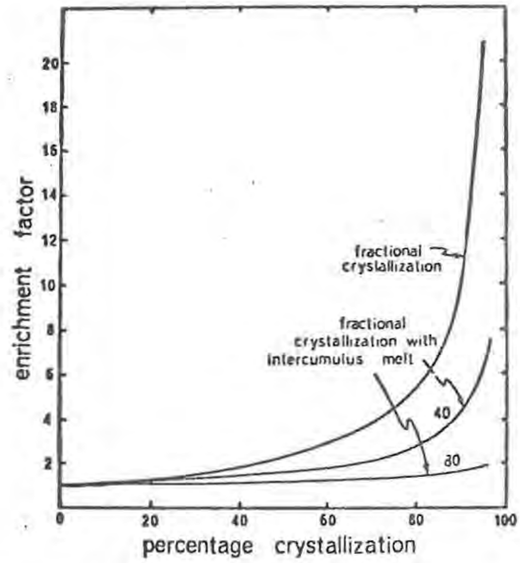


FIGURE 70: The affect of fractional crystallization with various proportions of intercumulate melt, during the crystallization of a calc-alkaline magma, on the enrichment of the incomptible elements (including water). A metalliferous hydrous phase would only develop during inactive tectonic periods with good crystal-melt separation (from Groves and McCarthy, 1978).

The interaction of hot dense metalliferous brines with cold seawater would result in the formation of an exhalative brine plume (Turner and Gustafson, 1978). The metals present in the brine would precipitate as sulphides to form bedded lensoid massive sulphides on the sea floor. Interaction between sediments saturated with seawater and the brine below the seawater-sediment interface would induce the early precipitation of the less soluble chalcopyrite and pyrite to form a cupriferous quartz-vein stockwork deposit. Polymetallic Kuroko-type and Archean-Type ore deposits and Besshi-type deposits are all associated with highly differentiated rhyolitic volcanics. Polymetallic deposits commonly occur adjacent to rhyolite domes towards the top of a calc-alkaline volcanic piles while Besshi-type cupreous-pyrite deposits are associated with relatively thin rhyolitic tuffs that overlie tholeiitic pillow lavas. Cyprus-type cypreous-pyrite deposits are, however, directly associated with tholeiitic pillow lavas in ophiolite complexes that show no indication of large-scale volcanic differentiation.

Polymetallic-type Volcanogenic Deposits

Polymetallic-type volcanogenic deposits consist of two main sub-types, the Archean-type and Kuroko-type, which are best developed in the Archean Abitibi Belt in the Superior Province of Canada, and in the Miocene-age Green Tuff Belt in Japan, respectively. In the Abitibi Belt volcanism appears to have been confined to central vent eruptions controlled by extensive rifts. Despite common features of general mafic to felsic trends, each domical centre constitutes a semi-independent volcanic assemblage of limited stratigraphic continuity. The mafic to felsic volcanic centres are concentrated into two major easterly trending bands approximately 80km wide that are separated by a median belt which is underlain by tholeiitic basalts and volcaniclastic sediments (Fig. 71).

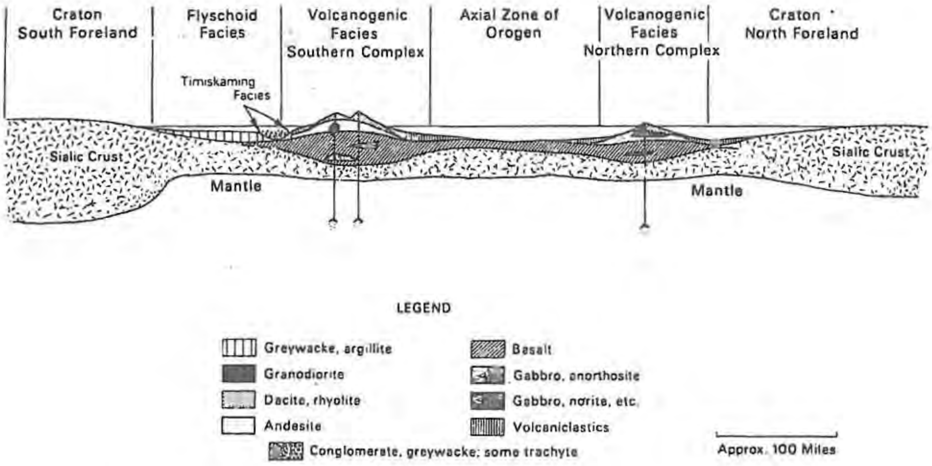


FIGURE 71: Hypothetical tectonic reconstruction of the Abitibi Belt from Noranda in the south to Matagami in the north (from Goodwin and Ridler, 1970).

Nine major and two minor volcanic complexes, originally between 90-160km in diameter have been delineated, each with a mafic to felsic volcanic sequence with associated gabbro and granodiorite intrusions (Fig. 72). The volcanics are thought to have developed near the rifted margins of an intra-cratonic basin. The central tectonically unstable trough was filled by volcaniclastic deposits while the adjacent marginal zones were

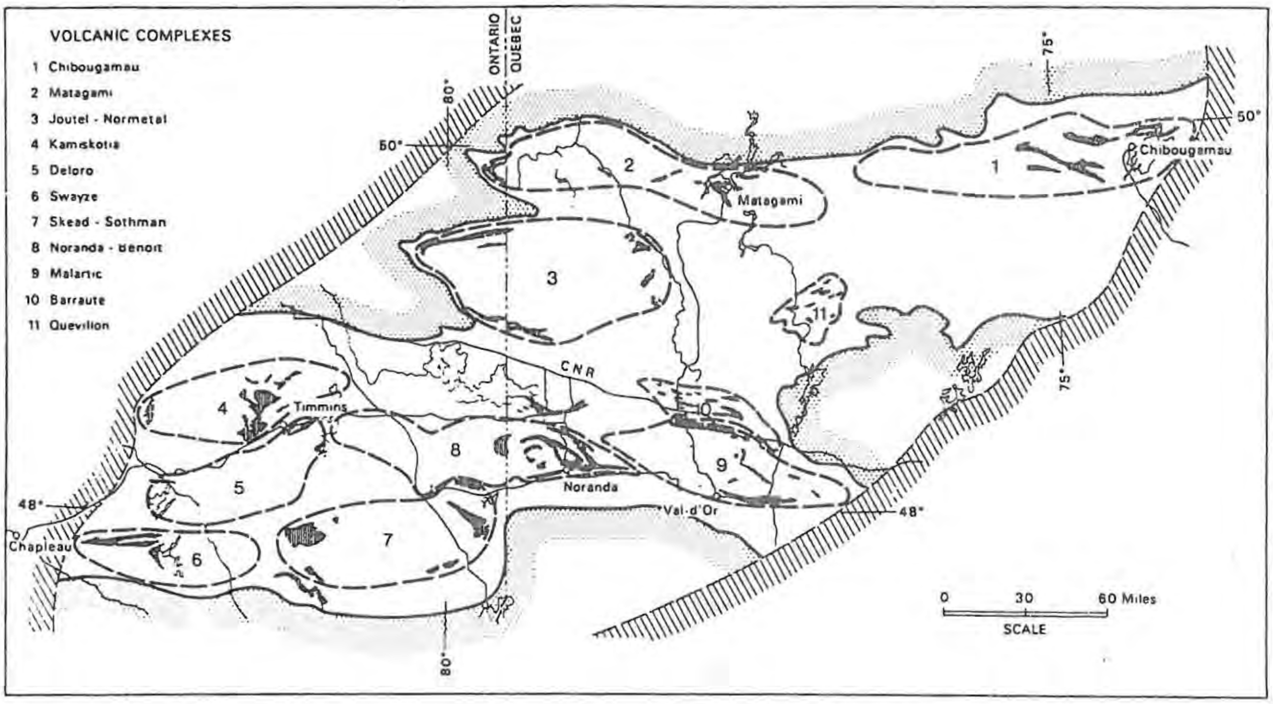


FIGURE 72: Distribution of volcanic complexes and associated felsic volcanics in the Abitibi Belt. Approximate boundaries of the volcanic complexes and co-genetic intrusions are shown by the dashed limes. The present elliptical shape is attributed to compressional folding (from Goodwin and Ridler, 1970).

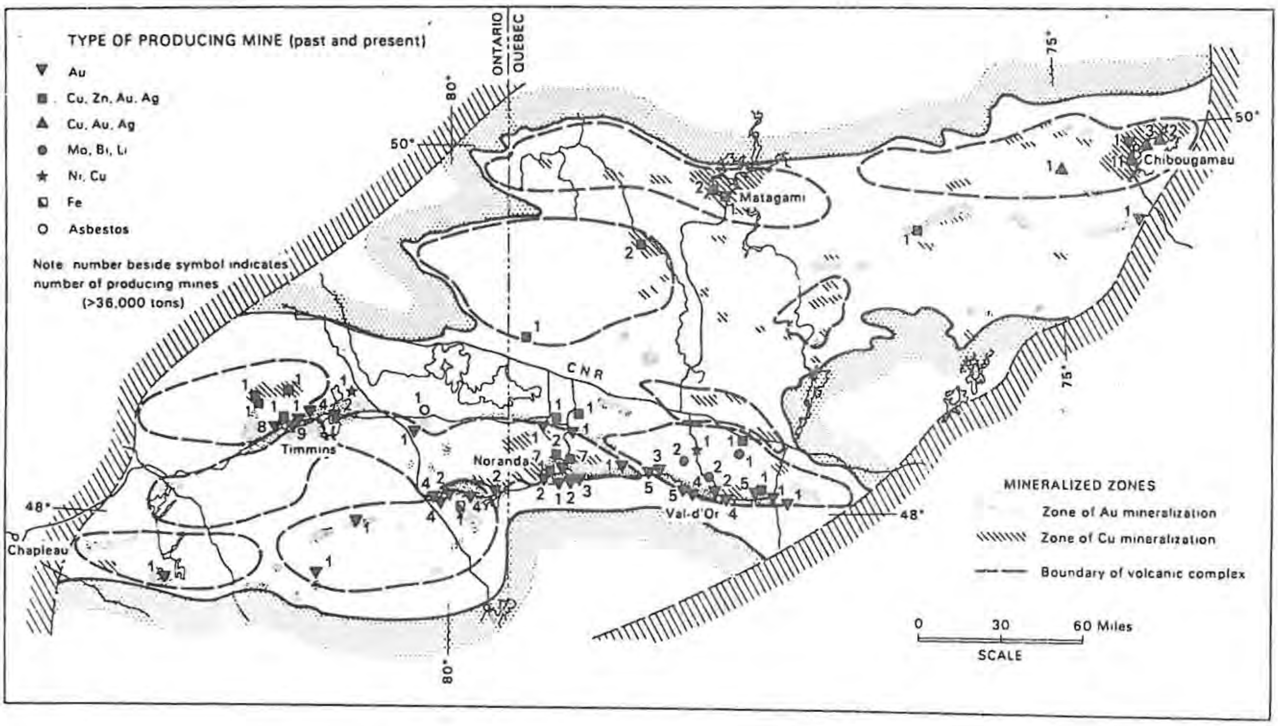


FIGURE 73: Metallogenic relationships in the Abitibi Belt (from Goodwin and Ridler, 1970).

dominated by sediments derived from the granitic basement. The lower parts of the volcanic assemblages are made up of tholeiitic lava flows and associated gabbroic intrusions. Some alkaline volcanics occur in some of the volcanic complexes. Andesitic lava flows and pyroclastics units intercalated with the tholeiitic basalts characteristically increase in proportion upwards. Volcanics of dacitic to rhyolitic compositions are generally present in the upper parts of the stratigraphy. Rhyolites, although they are only locally developed, show a very close spatial association with the major polymetallic volcanogenic deposits, such as the deposits at Noranda, Timmins and Matagami (Goodwin and Ridler, 1970).

The metallogenic patterns in the Abatibi Belt are intimately related to the volcanogenic patterns (Fig. 73). Volcanogenic polymetallic deposits have a direct genetic relationship with highly differentiated rhyolites. The majority of volcanogenic deposits are developed in the southern volcanic zone when compared to the corresponding northern zone. The north-eastern part of the belt also contains a significantly higher proportion of granitic batholiths (Goodwin and Ridler, 1970). It would therefore appear that the calc-alkaline magmas formed cauldron-type magma chambers, with associated intermediate to felsic volcanism in the south-western part of the belt, while the calc-alkaline magmas were to a large extent confined to diapiric plutons in the north-eastern part of the Abitibi Belt.

The Miocene Kuroko-type polymetallic deposits differ from the Archean-type volcanogenic deposits by the dominance of pyrite in the ore and the presence of associated hematitic cherts and sulphate deposits with the former deposits, in contrast to the dominance of pyrrhotite in the Archean-type deposits which are associated with graphitic tuftite units. The polymetallic volcanogenic deposits also tend to contain increasingly significant contents of lead with time. As a result, Archean-type polymetallic volcanogenic deposits are typically Cu-Zn-rich while Kuroko-type deposits are characterized by Cu-Pb-Zn-Ag-Ba-rich ores. The increase in the lead content is thought to be due to the progressive increas of radiogenic lead in the sialic crust with time. The absence of sulphates with the Archean-type polymetallic deposits and the change from sulphide-rich graphitic tuffites to hematitic cherts is thought to be due to the progressive build-up of the earths oxygen budget through time.

The Kuroko-type polymetallic deposits occur in the Green Tuff Belt that is confined to a narrow (±50km wide) elongate graben situated behind the present day subduction zone developed off the east coast of Japan (Fig. 74). The development of the trough started in the Early Miocene along structural trends that cross-cut the trends of the early Palaeozoic and Mesozoic geosynclines (Tatsumi, 1970). In the initial stages of basin development a large number of rift-bounded small sedimentary basins (±10-20km across), separated by near vertical transverse faults, formed in zones parallel to the trend of the island arc (Fig. 75). The horst and graben tectonism and local clastic sedimentation was then followed by rapid

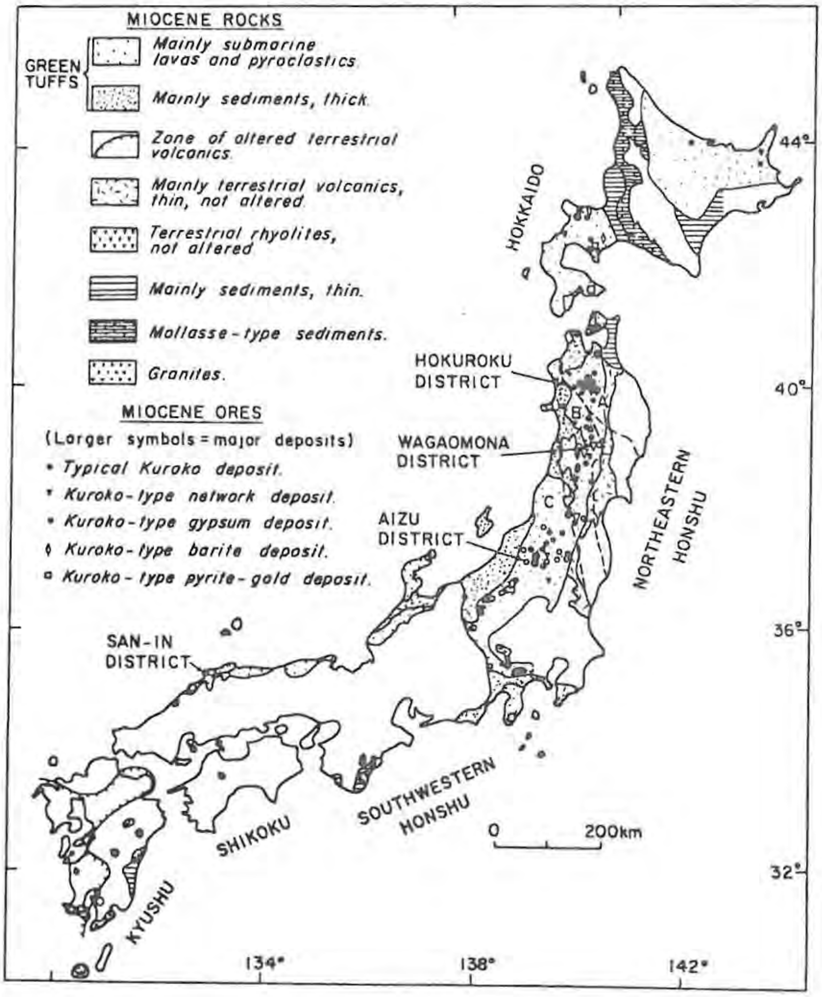


FIGURE 74: Distribution of the Miocene rocks and typical Kuroko deposits parallel to the trend of the subduction zone below Japan (see Fig. 58) (from Lambert and Sato, 1974).

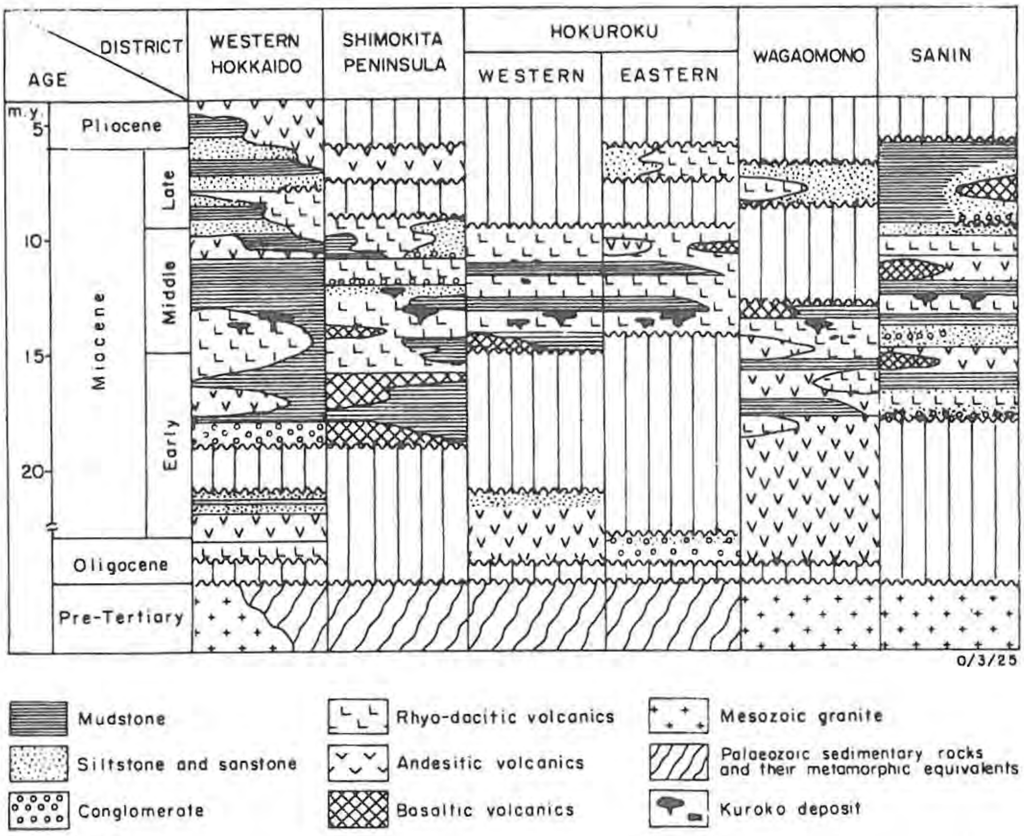
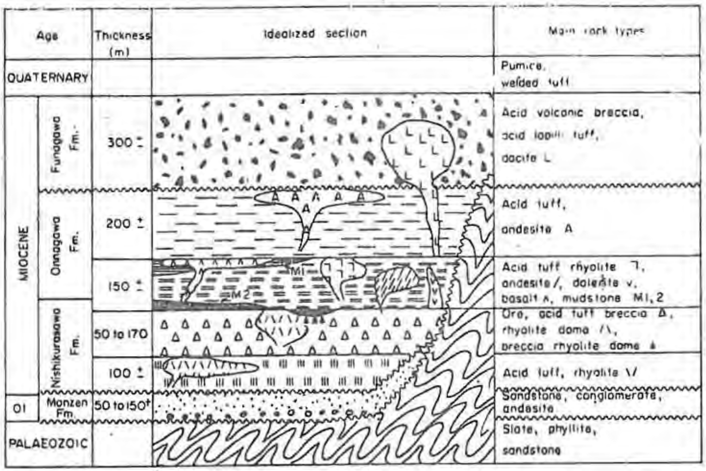


FIGURE 75: A comparison between generalized stratigraphic sections in the Green Tuff Belt illustrating the variable volcanic and sedimentary records due to differential subsidence in linked rift-bounded grabens (from Lambert and Sato, 1974).

subsidence and intense submarine volcanic activity, dominated by andesites in the early stages and dacites and rhyolites in the later stages. Greater than 1000m of volcanics and sediments were deposited in a series of linked basins which subsided differentially. On the adjacent highs sub-aerial arch volcanism was accompanied by the intrusion of small granite sub-volcanic plugs.

Kuroko-type mineralization is genetically associated with highly differentiated submarine rhyolite domes (Fig. 76). These rhyolite domes are concentrated in a narrow time interval throughout the whole 1200km Green Tuff Belt (Fig. 75), which is thought to coincide with the period when the trough reaches its maximum depth (Sato, 1970). The first intense volcanic phase was followed by a less intense period of mafic to felsic volcanism which became dominantly sub-aerial in the Plio-Pleistocene due to compressional uplift of the Green Tuff Belt.



A. Eastern part - Kosaka Mine area.

FIGURE 76: Schematic stratigraphic section through the area around the Kosaka Mine illustrating the close association of Kuroko-type volcanogenic ore deposits with differentiated rhyolite domes. Note that there is no apparent large-scale differentiation trend and that rhyolites occur above and below the ore body (from Lambert and Sato, 1974).

The Quaternary to recent volcanism can be shown to be directly related to the present day subduction zone by the progressive zonation from the tholeiitic basalt, high-alumina basalt to alkali olivine basalt away from the volcanic front (Fig. 58). The volcanic front is situated approximately 150km above the Benioff Zone. The present tectonic setting and associated tholeiitic volcanism has not changed significantly since the Miocene except for the intense generation of calc-alkaline lavas during the period between 25my to 7my. It is unlikely that this intense volcanism can be directly related to a change in the direction of the Pacific Plate, as suggested by Sato (1976), because the bend in the Hawaii-Emperior Volcanic Chain has been redated at 42my (Vogt, 1975). It is possible that rifting, graben formation and intense calc-alkaline volcanism is associated with the initiation of a secondary mantle diapir during a period of rapid subduction. The Quaternary to Recent volcanism can be directly related to the Benioff Zone suggesting that the present subduction rate is relatively slow, with a minor amount of partial melting of the mantle.

The Miocene volcanism associated with the Kuroko-type mineralization contains a significantly higher felsic to mafic ratio of 1:1,2 (Sato, 1976), compared to that of 1:13 for the Archean volcanics in the Abitibi Belt (Goodwin and Ridler, 1970). This probably reflects the more confined nature of the Green Tuff Graben behind the subduction zone and a corresponding increase in the crustal contribution to the calc-alkaline magmas, compared to the development of extensive mafic volcanism above the more permeable rift zones in the Archean. It is significant that the Kuroko-type mineralization is confined to such a narrow time interval. This could reflect relatively quiesent conditions at a tectonically inactive period that coincided with the maximum development of the trough and allowed relatively slow fractional crystallization to occur so that a metalliferous vapour phase could segregate from the differentiated calc-alkaline magmas. During periods of tectonic activity, magmatic differentiation and the concentration of the incompatible elements would be periodically disrupted.

There is a marked tectonic control on the distribution of Kuroko-type volcanogenic deposits in the Tasman Geosyncline in New South Wales. Kuroko-type volcanogenic deposits have an intimate relationship with extensive dacitic to rhyolitic volcanism in the Mid Silurian. The ore deposits are confined to a narrow marginal zone on the western boundaries of the Hill End and the Captains Flat Troughs, which are now preserved in major synclinorial zones (Fig. 77). These troughs were extensive rift-bounded basins filled with Ordovician greywackes and Late Ordovician andesitic volcanics. In the Mid Silurian extensive dacitic and rhyolitic volcanic activity was concentrated on the western margin of the trough and was particularly profuse adjacent to the cross-cutting Lachlan River Zone. (Fig. 77). To the north of this Fracture Zone, the Hill End Trough was filled mainly by volcaniclastic sediments derived from the felsic volcanism. Late Silurian felsic volcanics occur in the upper part of the sequence in this northern zone (Scheiber and Markham, 1976). In the Early Devonian the troughs were filled by greywackes and argillites with associated tholeiitic volcanism. Sedimentation was terminated by the Tabberabberan Orogeny in the Late Devonian that was followed by the intrusion of Carboniferous Granites.

The Kuroko-type mineralization is directly associated with the early felsic volcanics, except in the northern zone where the deposits are associated with the later volcanic phase. The deposits are located in close proximity to the faulted margin of the trough. The most important deposits are the Lake George and the Woodlawn deposits in the Captains Flat and Hills End Troughs respectively. The Lake George deposit is located in a narrow 2-8km wide graben that contains early conglomerates,

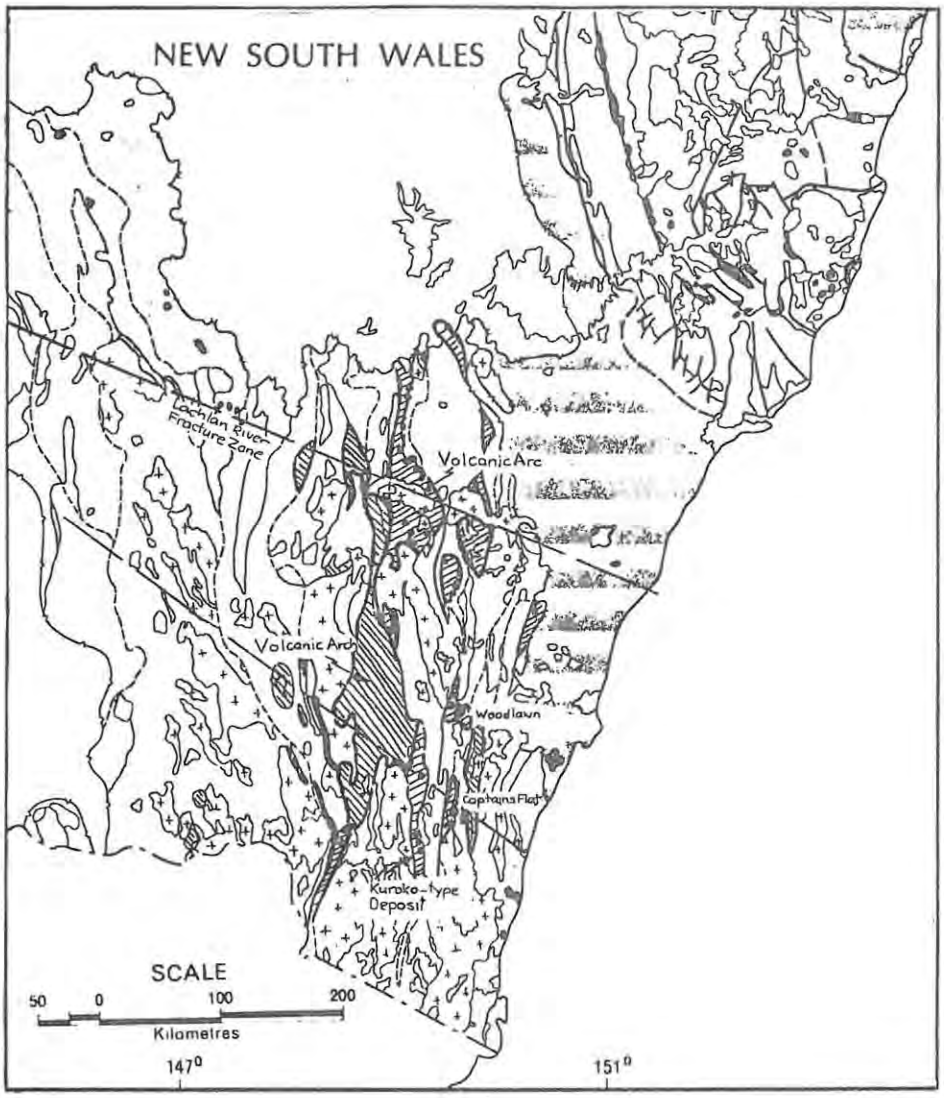


FIGURE 77: Tectonic map of portion of the Tasman Geosyncline in New South Wales showing the linear distribution of Ordovician-Silurian volcanics and associated Kuroko-type volcanogenic deposits on the western boundaries of the Hill End and Captains Flat Troughs. Volcanics are preferentially developed at the intersection with the Lachlan River Fracture Zone (compiled from Markham and Basden, 1974).

quartzites, siltstones and argillites that were probably deposited on a submarine fan complex. Sub-aerial volcanism occured to the west and east of the Hill End and Captains Flat Troughs on the Molong and Capertee Rises. Thick piles of calc-alkaline volcanics developed in these zones. Minor native copper deposits are associated with the sub-aerial volcanics. The intrusive granites are directly associated with the sub-aerial volcanics and together make up a typical Andean-type volcanic arch. During the subsequent orogenic deformation, the rift-bounded troughs were infolded to form synclinal zones while the adjacent volcanic arches formed the anticlinal zones. The anticlinal volcanic arches were as a result, more exposed to erosion. This is probably the main reason why porphyry copper deposits are not well developed in the Tasman Geosyncline, Although the tectonic setting would suggest that they should exist, because only the granitic root zones of the arches are now preserved.

Besshi-type Volcanogenic Deposits

Besshi-type cupreous-pyrite deposits are, in contrast to Cyprus-type deposits, associated with relatively thin tholeiitic volcanic units interbedded with thick volcaniclastic or epiclastic geosynclinal sediments. The Sanbagawa Belt in Japan was an area of late-stage tholeiitic volcanicity during the development of a Palaeozoic eugeosyncline that started in the Mid Silurian off the east coast of Japan. Late Carboniferous-Early Permian tholeiitic volcanics occur interbedded with the continentally derived greywackes in the upper part of a 10Km thick geosynclinal pile (Sugisaki, et al, 1972). Over a hundred cupreous-pyrite deposits, including the type example at Besshi, are known in the Sanbagawa Belt (Fig. 78). Although intermediate to felsic volcanism occured during the Silurian and Devonian the intense tholeiitic volcanic activity did not start until the Early Carboniferous. Alkaline volcanism which appears to occur marginal to the main zone of tholeiitic volcanic activity (Sugisaki, et al, 1972) was more prominant in the Devonian. Differentiated dunitic to gabbroic sills of various sizes are associated with the tholeiitic volcanics and pyroclastics. There is a pronounced antipathetic spatial relationship between the

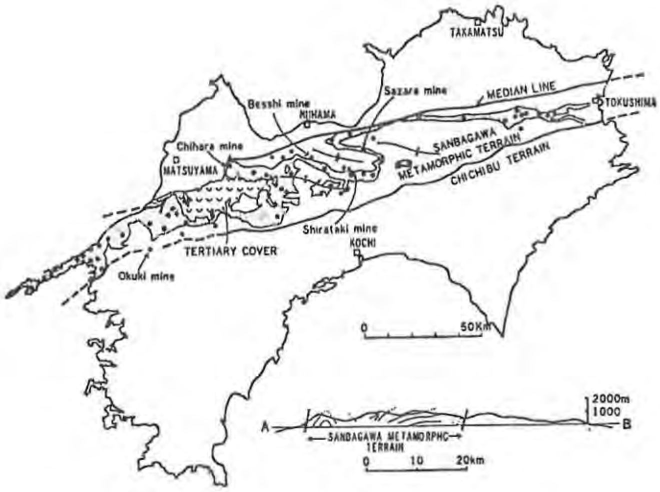
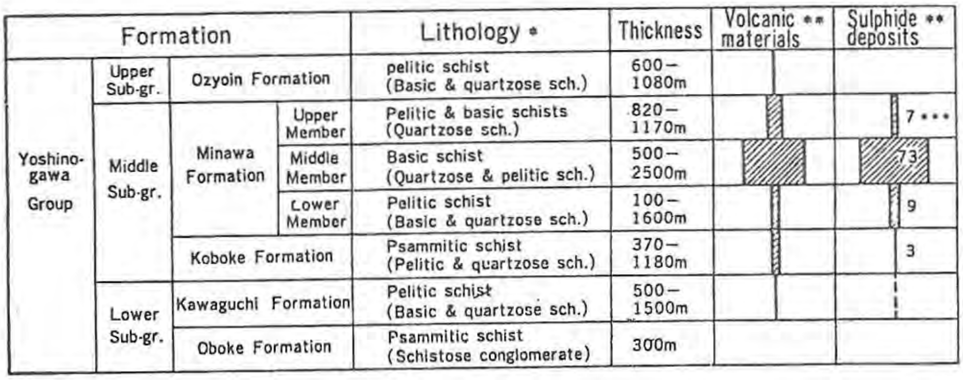


FIGURE 78 : The regional setting of Besshi-type cupreous-pyrite deposits in the Sanbagawa Belt. (from Tatsumi, et al, 1970).

cupreous-pyrite deposits and bedded manganese deposits that are both associated with the tholeiitic volcanism. The Besshi-type cupreous-pyrite deposits are concentrated in the Sanbagawa Belt, which was also the most volcanically active zone. There is a strong correlation between the intensity of volcanic activity in a particular stratigraphic section and the number of cupreous-pyrite deposits (Fig. 79) (Tatsumi, 1970). The eugeosyncline remained an active depository until the start of orogenic movement and regional metamorphism in the Later Permian.



Formation				Lithology *	Thickness	Volcanic ** materials	Sulphide ** deposits
Yoshino-gawa Group	Upper Sub-gr.	Ozyoin Formation		pelitic schist (Basic & quartzose sch.)	600–1080m		
	Middle Sub-gr.	Minawa Formation	Upper Member	Pelitic & basic schists (Quartzose sch.)	820–1170m		7 ***
			Middle Member	Basic schist (Quartzose & pelitic sch.)	500–2500m		73
			Lower Member	Pelitic schist (Basic & quartzose sch.)	100–1600m		9
		Koboke Formation		Psammitic schist (Pelitic & quartzose sch.)	370–1180m		3
	Lower Sub-gr.	Kawaguchi Formation		Pelitic schist (Basic & quartzose sch.)	500–1500m		
		Oboke Formation		Psammitic schist (Schistose conglomerate)	300m		

FIGURE 79: Stratigraphy of the Yoshinogawa Group in the Sanbagawa Belt illustrating the close association between the proportion of tholeiitic and rhyolitic volcanics and Besshi-type cupreous-pyrite deposits (from Tatsumi, et al, 1970).

Late Precambrian Besshi-type cupreous-pyrite deposits are developed in the Khomas Trough, an aulacogen that extends off the Damara Geosyncline in South West Africa. A narrow zone of tholeiitic volcanics is developed towards the upper part of a thick sequence of volcaniclastic greywackes. The cupreous-pyrite deposits are directly associated with rhyolitic tuffs and cherts that overlie the tholeiitic pillow lavas. Although only a single volcanic zone is developed, the cupreous-pyrite deposits appear to be distributed in clusters that might be a reflection of original volcanic centres. Differentiated dunite-gabbro sills are also closely associated with these clusters indicating that they were zones of pronounced magmatic activity.

Besshi-type deposits are also developed in the Early Cambrian Girilambone Beds of the Tasman Geosyncline in New South Wales. These cupriferous-pyrite deposits are associated with felsic volcanics, chert and quartz magnetite units that directly overlie basic volcanics. The basic volcanics are interbedded with metamorphosed sediments that were deposited in a trench complex. Differentiated dunitic to gabbroic sills are associated with clusters of small cupreous-pyrite deposits, of which the Girilambone deposit is the most significant (Schieber and Markham, 1976).

Besshi-type deposits are mainly confined to a period from the Late Precambrian to the end of the Palaeozoic and reflect a period of crustal history that is characterized by late-stage extensive crustal thinning in both eugeosynclinal troughs and in aulacogens that led to incipient crustal separation and confined tholeiitic volcanism.

Cyprus-type Volcanogenic Deposits

Cyprus-type cupreous-pyrite deposits are associated with tholeiitic pillow lavas in ophiolite complexes. Ophiolite complexes, consisting of a basal ultramafic cumulate zone, a central sheeted dyke complex and an upper pillow basalt sequence are obducted parts of oceanic crust formed along a mid-oceanic ridge. These deposits consist of poorly zoned massive chalcopyrite-pyrite deposits underlain by pyritic quartz-vein stockwork zones that grade into extensive zones of epidote-chlorite alteration, in contrast to the intensely altered pipes beneath Polymetallic and Besshi-type cupreous-pyrite deposits. The tholeiitic volcanics that underlie cupreous-pyrite deposits show no indication of large-scale magmatic differentiation which does occur in association with Besshi-type cupreous-pyrite deposits. It is thought that the Cyprus-type volcanogenic deposits are the result of the exhalation of geothermal brines onto the sea floor. These geothermal brines probably derived their metals content as a result of the interaction of hot seawater with tholeiitic volcanics at depth. Present-day heat flow studies suggest that much of the heat flow along the Mid-Atlantic Ridge is by hydrothermal convection, suggesting the presence of major geothermal systems.
Ordovician-age Cyprus-type deposits are developed in the Appalachian Geosyncline in New Foundland. Cyprus-type deposits in the Tasman Geosyncline are associated with Mid-Devonian ophiolite complexes. The type examples are the Mesozoic Cyprus deposits in the Alpine Fold Belt. Stratigraphic correlations on Cyprus suggest that the major cupreous-pyrite deposits are developed on a number of stratigraphic levels, each one associated with a separate phase of submarine tholeiitic volcanism (Fig. 80). (Constantinou, 1976). There is no indication of magmatic differentiation. Slow spreading mid-oceanic ridges appear to be characterized by tholeiitic basalts with less than 1% TiO_2. Although it may be coincidental, the

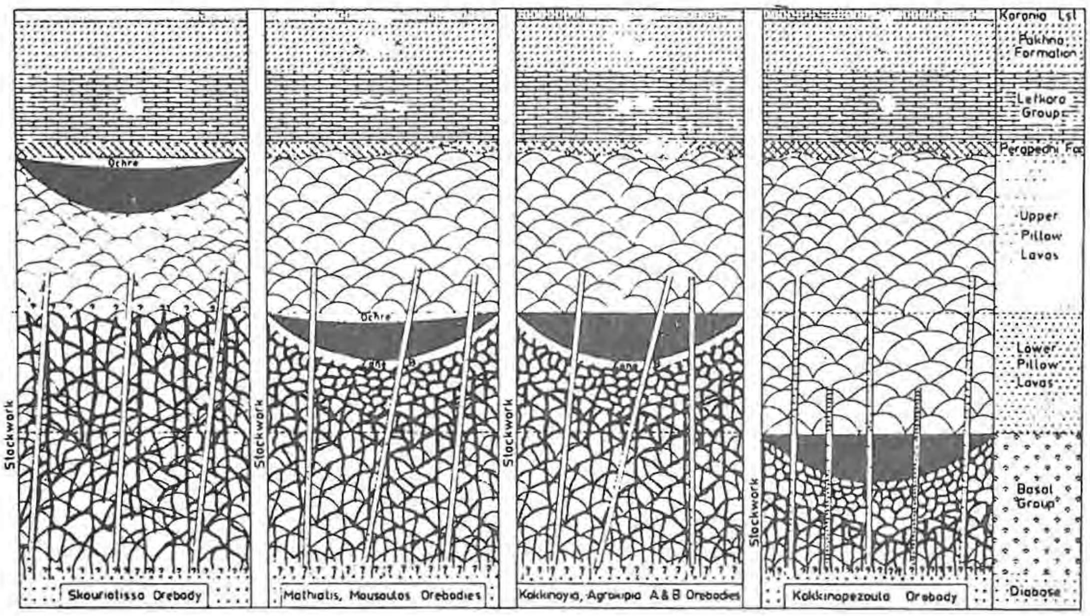


FIGURE 80: Schematic sections showing the correlation between different Cyprus-type cupreous-pyrite deposits in the Troodos Ophiolite Complex and the development of extensive stockwork deposits below the massive sulphide lenses (from Constantinou, 1976).

tholeiitic basalts associated with the Cyprus deposits contain 1% TiO_2 suggesting that Cyprus-type massive sulphide deposits are associated with slow spreading centres (Schieber and Markham, 1976), that would enable large geothermal convection cells to develop. The interaction of these metalliferous geothermal brines with cooler seawater would initiate sulphide deposition in a similar manner caused by the interaction of brines derived by magmatic differentiation, with seawater.

In the Appalachian Geosyncline the Cyprus-type deposits show a close spatial relationship with Silurian and Devonian polymetallic Kuroko-type volcanogenic deposits (Fig. 81). It is possible that these Cyprus-type deposits are associated with profuse volcanism in response to extreme horizontal extension and sea-floor spreading, following the extensive calc-alkaline volcanic activity in the Silurian-Devonian and the associated development of polymetallic Kuroko-type deposits (Windley, 1977).

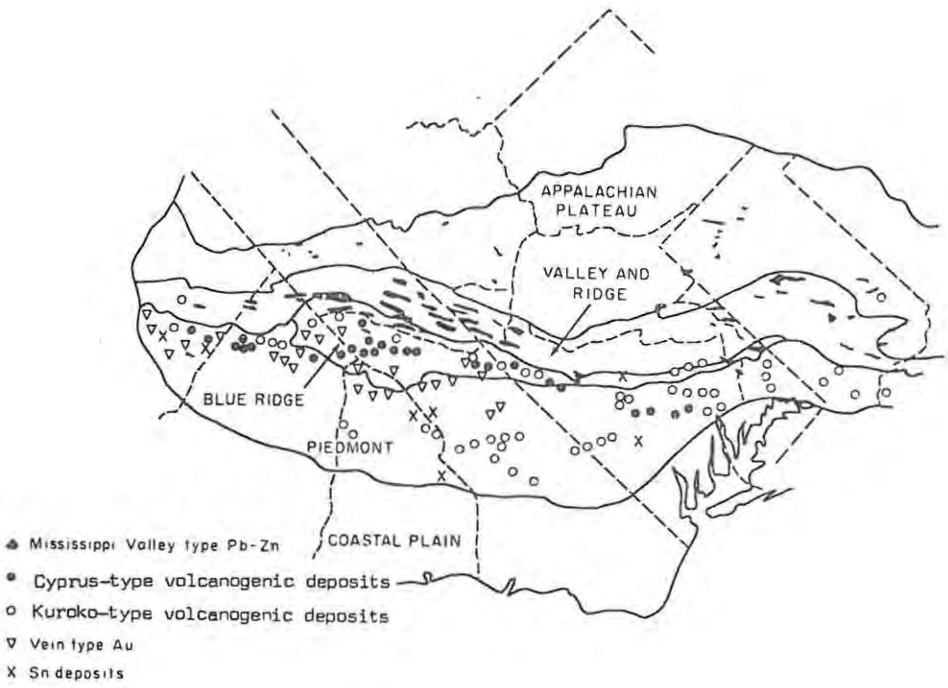


FIGURE 81: Metallogenic zonation patterns in the Appalachian Geosyncline, North America illustrating the close association of Cyprus-type cupreous-pyrite deposits with Kuroko-type volcanogenic deposits. Note a definite tendency of the Cyprus-type deposits to occur in the middle of the zone of Kuroko-type volcanogenic deposits (from Windley, 1977).

VOLCANOSEDIMENTARY DEPOSITS IN AULACOGENS AND TROUGHS

The Rosh Pinah Ore Deposit

The Late Proterozoic Gariep Group forms part of the Pan-African Orogenic Cycle in South West Africa. The Gariep Group consists of a sequence of volcanics and sediments that were deposited in a rapidly subsiding trough controlled by north-north-westerly trending faults. Rhyolites, felsic pyroclastics and volcano-clastic sediments and minor basaltic pillow lavas are developed near the base of a sedimentary sequence. Thick diamictites fill local paleo-topographic lows in the basement below the volcanics and are also interbedded with thick sequences of greywackes and allodapic limestones (McMillan, 1968). The sediments are thought to have been deposited on a submarine fan, the diamictites and coarse-grained clastics were deposited in the proximal fan facies while the fine-grained argillaceous sediments and allodapic limestones were deposited in the distal fan facies (Dingemans, 1976). Although during the initial stages of the development of the trough, volcanic activity contributed a significant proportion of the detrital material, most of the coarse clastic material was derived from the basement to the east. The carbonate in the persistant allodapic carbonate horizons were derived from the adjacent carbonate shelf and re-deposited by turbidity currents. Two general coarsening-up cycles, which also change laterally from predominantly proximal facies in the east to distal facies in the west can be recognized. These lateral and vertical facies variations suggest that the progradation of the submarine fan was controlled by uplift of the easterly source area along the major faults.

The Rosh Pinah ore deposit is hosted by a sequence of coarse-grained volcaniclastic turbidites that grade upwards into, and are interbedded with, thin siltstones and carbonaceous shale horizons. The mineralization is interbedded with a sequence of finely bedded carbonaceous shales (or tuffites) and cherts with interbedded poorly graded crystal tuff bands. Finely banded pyrite, sphalerite and galena are rhythmically interbedded with the laminated carbonaceous shales. Thickly banded massive sulphide lenses, consisting mainly of pyrite, sphalerite and galena in a carbonate and barite matrix, are associated with banded chert and barite lenses within the ore zone (Page and Watson, 1976). The underlying volcaniclastic tuffs are commonly intensely brecciated. These breccia zones are typically silicified and veined by carbonate and contain minor disseminated pyrite and chalcopyrite.

The Rosh Pinah ore deposit is directly associated with the calc-alkaline volcanism that was associated with the initial subsidence of the Gariep Trough. The ore deposit is localized on the margin of the trough, which is probably close to an original bounding-rift as the Gariep Group lenses out rapidly onto the basement to the east and in places the eugeosynclinal facies grades vertically into the miogeosynclinal continental sandstones and shallow marine sediments of the Nama Supergroup to the east (Dingemans, 1976). Although the ore deposits are spatially associated with rhyolite flows, the mineralization is not directly related to rhyolite domes that is typical of central-vent Kuroko-type volcanogenic deposits. The mineralization is confined to a thick carbonaceous shale sequence, which represents deposition during a quiesent period with diminished volcanic activity and a paucity of continentally derived detritus. The dominance of differentiated calc-alkaline volcanic activity with minor basic volcanism indicates that the ascent of mantle-derived basaltic magmas was confined and as a result restricted to major faults. The assimilation of crustal material during ascent and subsequent in situ fractional crystallization led to the formation of a rhyolitic magma which was extruded during the initial subsidence of the trough. Fractional crystallization had also built up the incompatible elements to such a degree that a metalliferous magmatic brine was generated during the early stages of volcanic activity. The alteration in the footwall, mainly silicification and carbonate veining, indicates that the metalliferous brines were mainly low temperature and therefore derived from a differentiated calc-alkaline plutonic complex at depth. During the ascent of the metalliferous brines, most of the copper was probably deposited in response to cooling of the brine. As a result, there was an effective separation of Pb-Zn-Ba-Ag from the copper, so that only minor chalcopyrite occurs in the footwall breccia zone. The lead-zinc mineralization was deposited under reducing conditions,as indicated by the interbedded carbonaceous shales, in the trough and periodically interrupted by the introduction of continentally derived argillaceous material and volcanic ash. The Rosh Pinah ore deposit is a typical volcano-sedimentary deposit that shows a close spatial relationship with calc-alkaline volcanism.

The McArthur River and Mount Isa Ore Deposits

The Mid-Proterozoic McArthur River lead-zinc, and Mount Isa Copper lead-zinc ore deposits are hosted by a volcano-sedimentary sequence. The 1800-1500my old Carpentarian volcanics and sediments lie uncomformably over large areas of the Mid Proterozoic Australian Craton, which has remained relatively stable since the wide-spread ±1800my plutonic and volcanic event comparable to the Hudsonian Orogeny of Canada. The preserved Carpentarian rocks consist of essentially underformed and unmetamorphosed platform sediments which are best developed in the McArthur Basin. Equivalent deformed and metamorphosed sediments and volcanics are situated in the Mount Isa Geosyncline on the south-east extension of the McArthur Basin (Fig. 82) (Dunnet, 1976). The McArthur Basin is transected by the fault-bounded intra-cratonic Batten Trough which possibly extends under Phanerozoic cover into the Paradise Rift in the Mount Isa area. These rift-bounded troughs influenced the facies distribution and thickness of the sedimentary and volcanic succession during deposition. The major base metal deposits are also confined to these rift-bounded troughs (Fig. 83).

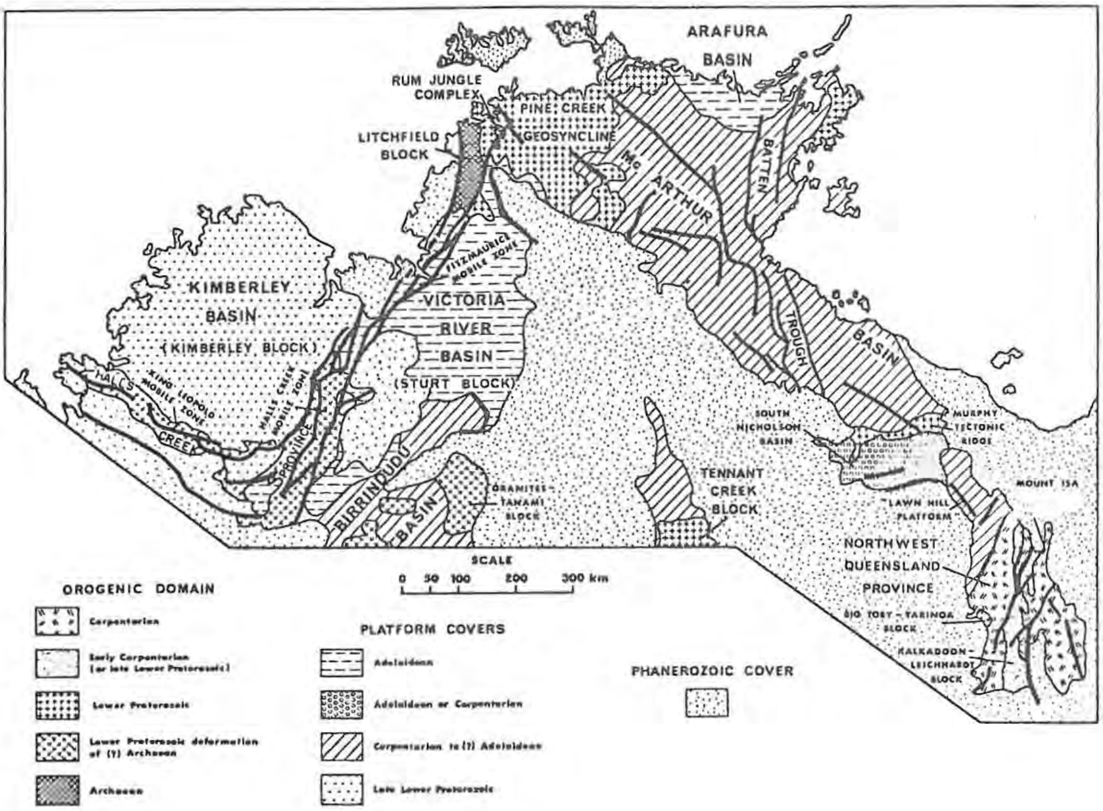


FIGURE 82: The regional setting of the Mid Proterozoic McArthur Basin and Mount Isa Geosyncline in the Northern Territory, Australia (from Plumb and Derrick, 1975).

The deposition of Mid-Proterozoic volcanics and sediments in the platform-type McArthur Basin was dominated by the 1300km north-south trending intra-cratonic Batten Trough. The lower Tawallah Group is dominated by continental quartzites with subordinate basic volcanics, carbonates and shales. The deposition of the basal clastic sediments, derived from continental sources to the east and west, was followed by widespread sub-aerial flood basalt volcanism. Periodic reactivation of the source areas is indicated by several local uncomformities. The volcanics and interbedded continental clastic sediments are overlain by a sequence of shallow marine quartzites, shales and carbonates (Plumb and Derrick, 1975). The Tawallah Group is overlain by the predominantly carbonate sediments of the McArthur Group. The Batten Trough was active throughout deposition of the Carpentarian sediments, although it only reached its full development in the McArthur River area during the deposition of the McArthur River Group (Plumb and Derrick, 1975). Later deformation on the platform was most intense in the Batten Trough with

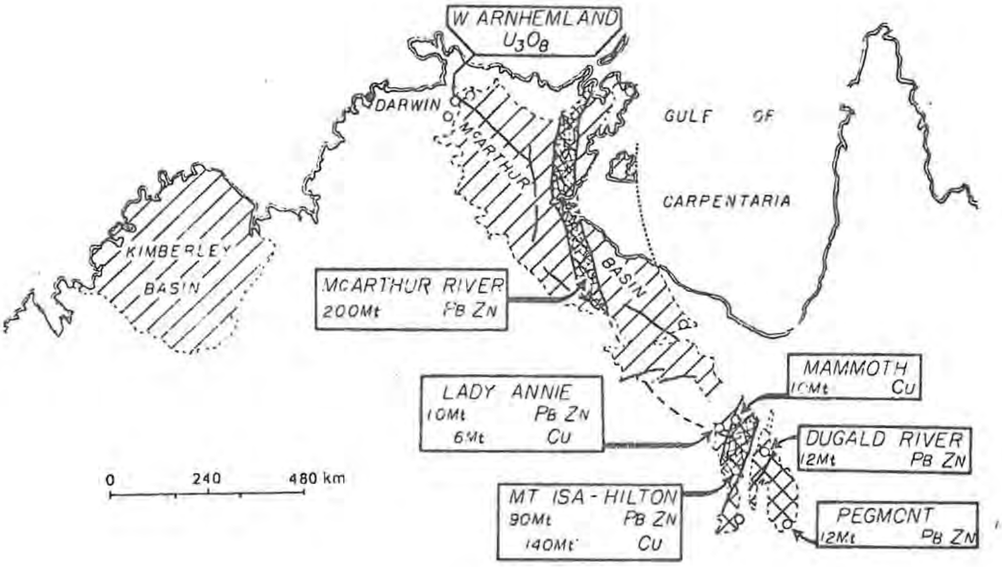


FIGURE 83: The distribution of major Mid Proterozoic base metal deposits in the McArthur Basin and Mount Isa Geosyncline, Norther Territory, Australia.

large-scale block faulting and uplifting of the trough into a major horst block while the adjacent platform sediments were essentially undeformed. The platform shelves were largely an area of slow deposition of mainly supratidal, intertidal and shallow subtidal stramatolitic carbonates, while the trough was the site of active subsidence and the deposition of basinal dolomitic siltstones and shales in relatively deep water. Over 3600m of fine-grained dolomitic siltstones and carbonaceous shales were deposited in the trough, in contrast to less than 300m of stramatolitic carbonates on the adjacent shelves (Dunnet, 1976).

A major marine transgression on the platform was accompanied by local subsidence and the deposition of considerable tuffaceous material with the carbonaceous dolomitic shales in the deeper Batten Trough. The maximum tuff deposition occured in a period just prior to the formation of the syngentic McArthur River base metal deposits on the active eastern edge of the Batten Trough (Crohn, 1975). The base metal deposits are confined to the HYC Pyritic Shale Member which is preferentially developed in the local Bulburra Depression which formed adjacent to the Emu Fault, the boundary rift of the Batten Trough. The rate of subsidence of the floor of the Bulburra Depression was uneven and resulted in the development of several sub-basins. These sub-basins are characterized by a thicker development of the HYC Pyritic Shale Member and by the development of stratiform-base metal deposits. They HYC Ore Body is the most important lead-zinc ore deposit and is confined to the "HYC Depression", while minor sub-economic mineralization is developed in the "W-Fold" and "Mitchell Yard" sub-basins. Outside the sub-basins the HYC Shale consists of weakly pyritic and carbonaceous bedded shales, devoid of base metal accumulations, that rapidly thin towards the edges of the Bulburra Depression and progressively become more dolomitic, less pyritic and less bituminous (Crohn, 1975). The HYC Shale is bordered to the east of the shelf line by the Cooley Dolomite Member (Fig. 84). The Cooley Dolomite Member consists of massive, brecciated and stramatolitic dolomite flanked by slump breccias that interfinger with the HYC Shale. The HYC Shale contains graded beds on both a micro-scale and a macro-scale and represents a sequence of allodapic dolomites and interbedded shales. The dolomitic silts and turbiditic breccias were derived from the adjacent carbonate shelf and redeposited by tubidity currents in the Batten Trough.

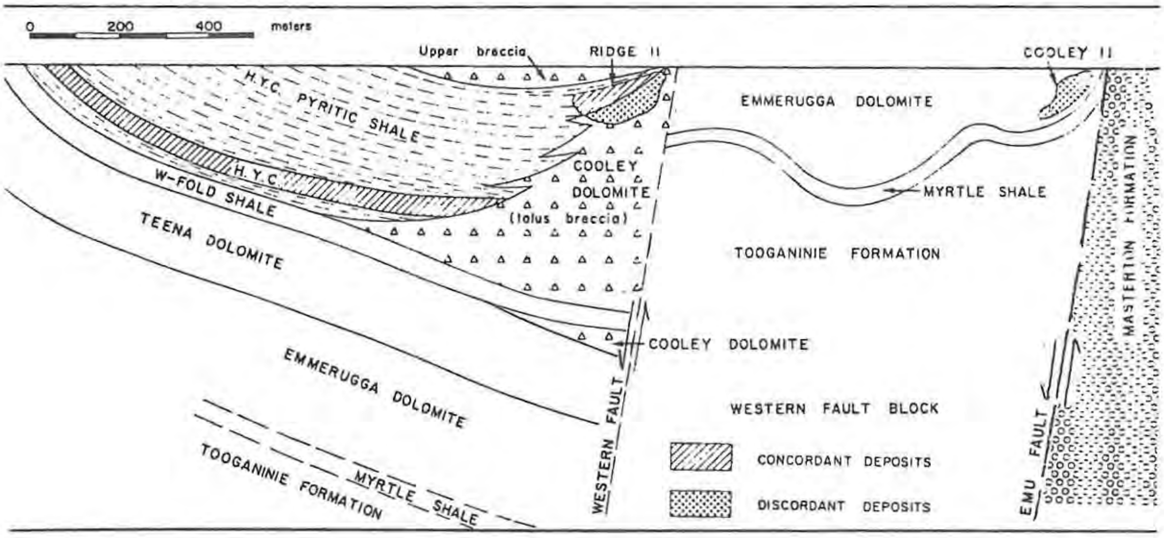


FIGURE 84: Schematic cross-section through the McArthur River Ore Deposits illustrating the major facies associations on the eastern margin of the Batten Trough and the development of the stratiform HYC Lead-Zinc Deposit, and discordant Ridge II and Cooley II deposits (from Williams, 1978).

The HYC Shale in the "HYC Depression" contains seven mineralized shale beds and six lower-grade more dolomitic horizons. The lead values drop off markedly along strike, while the zinc values extend laterally outwards and gradually fall off with pyrite extending even further. Other discordant mineralized zones of low-grade zinc (Ridge 1), lead with minor copper (Ridge II) and discrete lead-rich (Cooley 1) and copper-rich deposits (Cooley 11) are developed in the Cooley Dolomite Member marginal to stratiform mineralization in the "HYC Depression" (Fig. 85). (Murray, 1975). The coarse-grained discordant mineralization occurs in veins and in disseminated to massive patches in the host breccias that were deposited in open-spaces in the dolomite breccia. Lateral and vertical variation in the metal ratios suggest that mineralizing solutions were exhaled from the Emu fault. The early precipitation of chalcopyrite in the Cooley 11 effectively removed most of copper from the metalliferous brines so that the other deposits are progressively enriched in lead and zinc away from the fault (Fig. 85) (Williams, 1978).

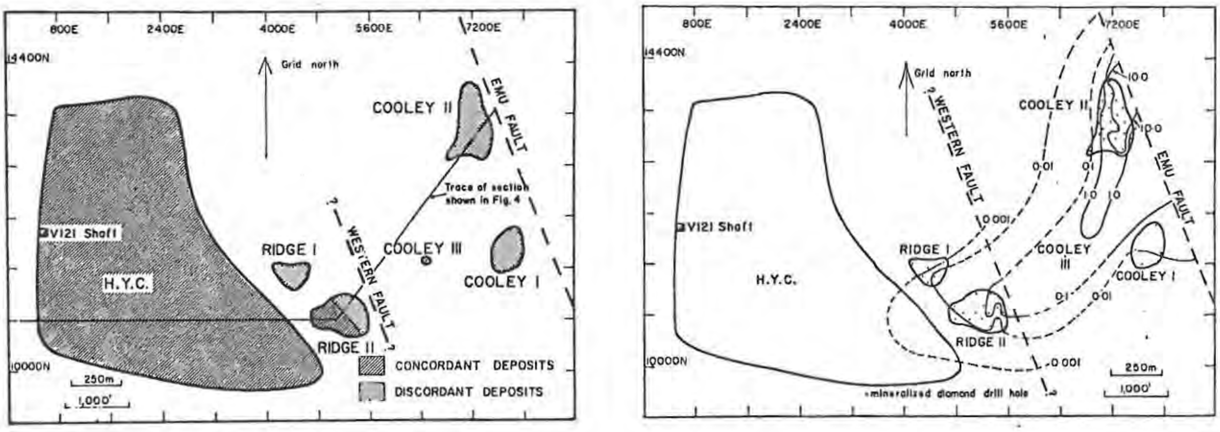


FIGURE 85(A): Distribution of discordant and concordant deposits at McArthur River. (B): Overall base metal zoning in the Cooley and Ridge Deposits, shown by atomic ratio Cu/(Pb + Zn) contours. The zonation suggests that the mineralizing fluids were exhaled along the Emu Fault and that rapid precipitation of copper in the Cooley II deposit effectively separated copper from the metalliferous brines. The conformable HYC Lead-Zinc Ore Deposit precipitated from stable metalliferous brines under reducing conditions (from Williams, 1978).

The Mount Isa Geosyncline in the north-west Queensland Province contains stratigraphic equivalents of the McArthur Basin which can be subdivided into four main structural units (Fig. 86). The north-western Platform is characterized by relatively flat-lying unmetamorphosed continental and shallow marine sediments similar to the Tawallah and McArthur Groups. As the Miogeosyncline is approached, particularly in the narrow 15-30km wide graben, the Paradise Rift, the sedimentary sequence thickens and tholeiitic volcanics become more prominant. The Paradise Rift is not a single fault-bounded trough , but rather a series of normal faults that are symmetrical about the Paradise Rift. These represent a continuation of early structures from the platform into the miogeosyncline and therefore

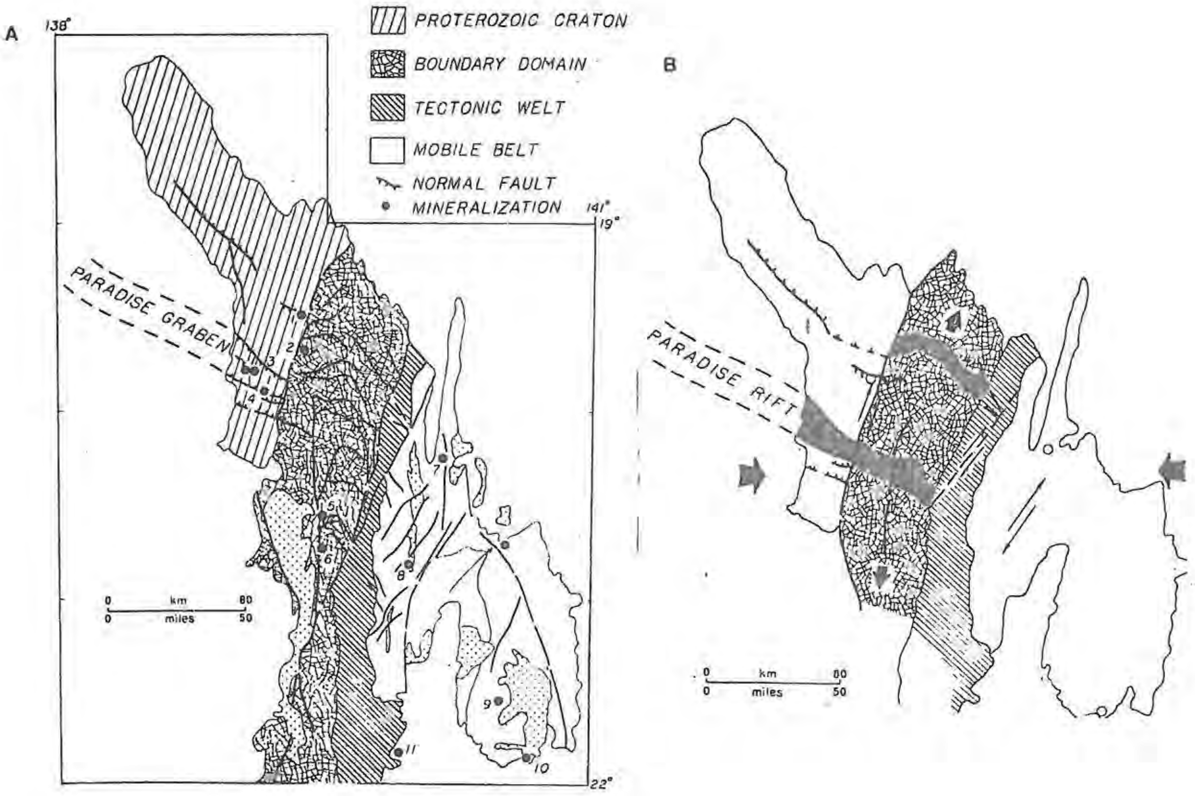


FIGURE 86: The four major structural domains in the Mount Isa Geosyncline and the fragmented aulacogen - the "Paradise Rift". (A) Present geometry of the Mid Proterozoic rocks with location of Lady Annie-Lady Lorette (3), Mount Isa (6), Hilton (5), Dugald River (8) and other significant base metal deposits adjacent to major faults. (B) Reconstruction of the Mount Isa Geosyncline by removal of major displacement on right lateral faults. Note the localization of basic volcanics and mineral deposits within the "Paradise Rift" aulacogen (from Dunnet, 1976).

the Paradise Rift is in effect an aulacogen.

Eight major stratiform base metal deposits are known in the Mount Isa Geosyncline. The copper deposits are restricted to the tholeiitic volcanics in the immediate vicinity of the miogeosyncline, while the lead-zinc deposits show a wider geographic spread (Dunnet, 1976). The Lady Loretta lead-zinc and Lady Annie copper deposits occur in the shelf sediments of the Platform on the extension of the Paradise Rift. These deposits are located close to the transition between shallow water stramatolitic carbonates to the north-east and a basinal sequence of dolomitic siltstones and sandstones, with minor thin tuff bands (Plumb and Derrick, 1975). Weak mineralization is developed over a stratigraphic section of 500m. The base metal sulphide accumulations are restricted to thin pyritic shale bands at the top of individual graded beds. The metal values are highest in the shale bands due to the relatively long quiesent periods between the cyclic influxes of silt and sand. The single 24m ore horizon within the mineralized sequence is hosted by a zone of finely laminated shales that represent a period of minor clastic influx during exhalative activity (London, et al, 1975).

The Mount Isa copper-lead-zinc and Hilton lead-zinc deposits are developed close to the Mount Isa Fault. The ore deposits are confined to the Urquhart Shale, a carbonate-rich black shale with persistant felsic tuff bands. These carbonaceous shales occur at the top of a thick sequence of dolomitic siltstones. All the mineralization is confined to a central zone of the finely laminated pyritic Urquhart Shale. The stratigraphy at the Hilton Mine along strike is a duplicate, although condensed sequence of that developed at Mount Isa Mine. Similarly the mineralization at Hilton is restricted to a narrower stratigraphic section (110-210m) than the mineralization at Mount Isa which occurs over an interval of 1050m, although the main ore bodies are restricted to the upper 650m (Mathias and Clark, 1975).

At Mount Isa, two distinct ore types are present; the copper-rich ore zones are confined to the "silica dolomite", while the lead-zinc-rich ore zones occur within the finely laminated Urquhart Shale (Fig. 87). Galena, sphalerite, pyrite and pyrrhotite occur as distinct laterally persistant bands in the graphitic shale. Individual lead-zinc ore zones can reach 4500 x 1000 x 1000m in extent. Although isolated mineralized beds occur throughout the stratigraphic section, it is only where these bands are grouped together in sufficient density that they constitute an ore zone. Fourteen major lead-zinc ore zones are present in the Mount Isa Mine. Coarse-grained chalcopyrite is confined to quartz and carbonate veins within a silicified shale breccia, the "silica-dolomite". The seven copper ore bodies have an en-echelon pattern the commonly interfinger at their southern and lower extremes with the lobes of "silica dolomite". These ore zones can reach up to 530m wide with a strike of greater than 2600m (Mathias and Clark, 1975).

The stratiform galena-sphalerite ore bodies are the only mineralized zones developed at the Hilton Mine. Seven ore horizons are present in the Urquhart Shale. Some of these ore zones are essentially massive sulphide beds associated with intergranular silica, while other ore zones consist of finely interlaminated sulphides and graphitic shale (Mathias, et al, 1973). No significant mineralization is associated with the siltstone-rich zones within the Urquhart Shale. The grade of the ore zones depends on the amount of interbedded shale, which indicates that ore zones only

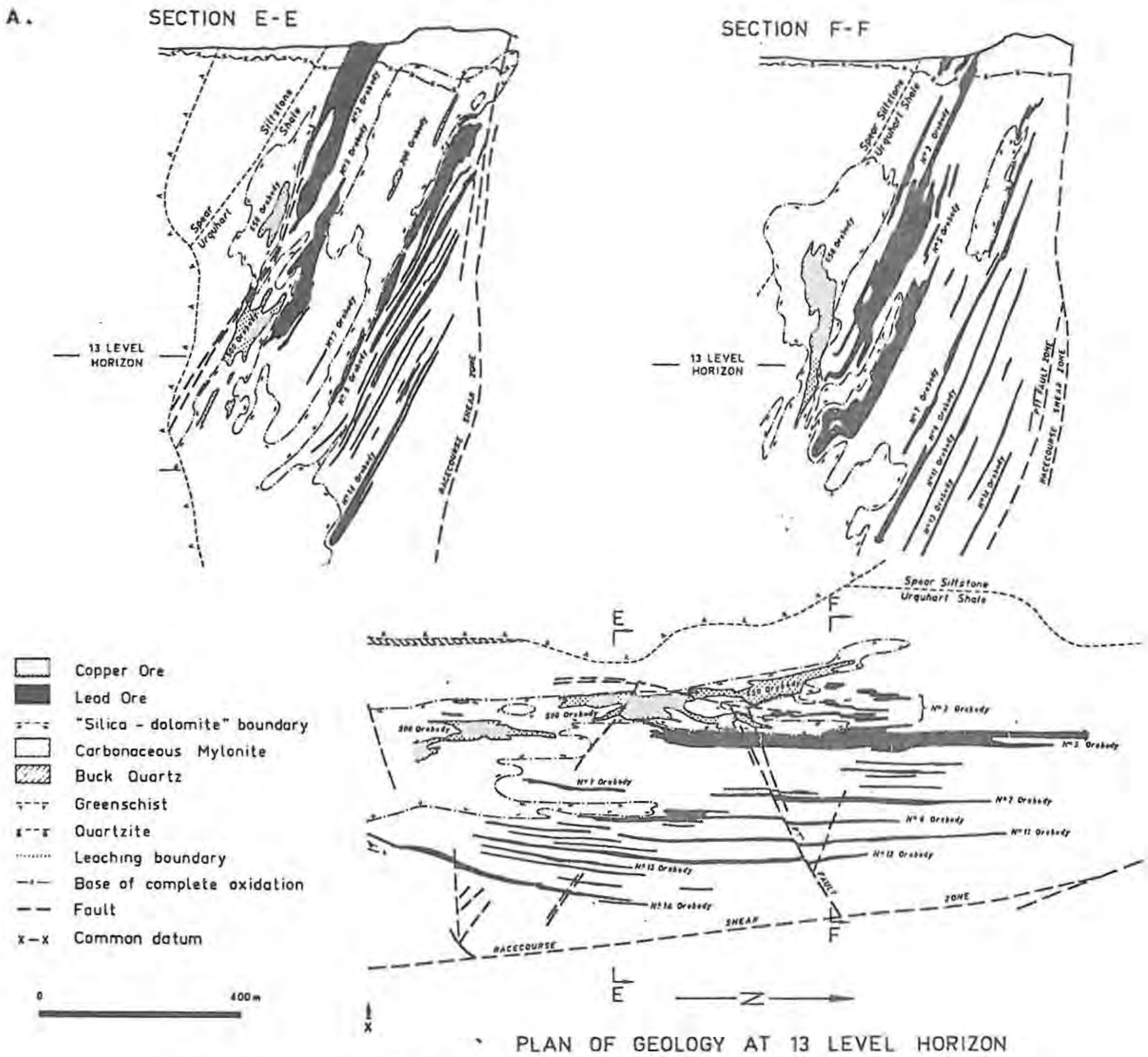


FIGURE 87A: Typical plan and cross-sections through the Mount Isa Ore Deposit showing the development of concordant lead-zinc-rich ore bodies within the Urquhart Shale and discordant copper-rich ore bodies within the "Silica dolomite" (from Mathias and Clark, 1975).

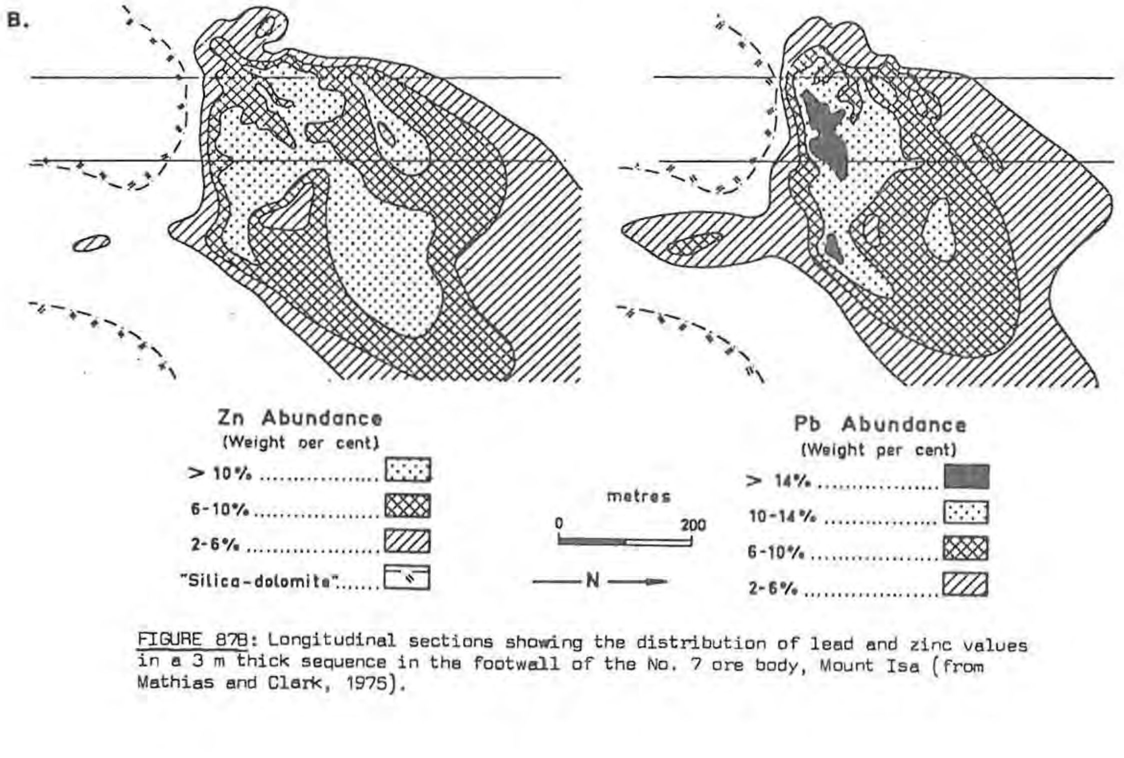


FIGURE 87B: Longitudinal sections showing the distribution of lead and zinc values in a 3 m thick sequence in the footwall of the No. 7 ore body, Mount Isa (from Mathias and Clark, 1975).

developed during quiescent periods, characterized by a lack of influx of clastic or volcaniclastic detritus. The ore zones formed by the precipitation of lead and zinc from metalliferous brines under reducing conditions, as is indicated by the presence of graphitic shales.

Over two thousand copper occurrances are also known in the Mount Isa area. These occurrances are concentrated in three stratigraphic zones. The majority of copper deposits occur as vein networks within minor faults in the basal amydaloidal basalts and in the stratigraphic equivalents of the Cliffdale Volcanics. The richer deposits are typically developed at the intersection of two faults. A significant number of copper occurrances occur in the stratigraphic equivalents of the Urquhart Shale. Chalcopyrite also occurs in veins within scapolite-rich metamorphosed clastic sediments (Wilson, et al, 1972). Porphyroblastic scapolite and scapolite veining is common particularly adjacent to the black shale-hosted Dugald River lead-zinc deposit (Whitcher, 1975). These scapolite zones are thought to represent metamorphosed sediments that were originally saturated by sodium-rich brines, probably associated with the mineralization. The early deposition of epigenetic copper deposits effectively separated copper and lead-zinc so that some volcano-sedimentary deposits contain only lead and zinc (Hilton), while others contain adjacent copper-rich and lead-zinc-rich ore deposits (Mount Isa).

The Sulivan Ore Deposit

The Sulivan ore deposit is the largest of several stratiform lead-zinc ore deposits developed within the Aldridge Formation of the Purcell Supergroup in the Kimberley area of British Columbia (Fig. 88). The Late Proterozoic sediments and volcanics of the Purcell Supergroup, and equivalent Belt Supergroup to the south, were deposited in narrow confined basins on the western margin of the North American Craton. A thick 11km sequence of sediments and volcanics were deposited in the northerly trending basin and in a narrow rift-bounded aulacogen which extends for 450km into the craton (Kanasewich, 1968). The Sulivan ore deposit is located on the northern boundary of the continuation of the aulacogen into the basin. The ore deposit itself is truncated by the east-west bounding Kimberley Fault which has a throw of 3000m. The ore deposit is localized by the intersection of the northerly trending Sulivan Fault with the Kimberley Fault.

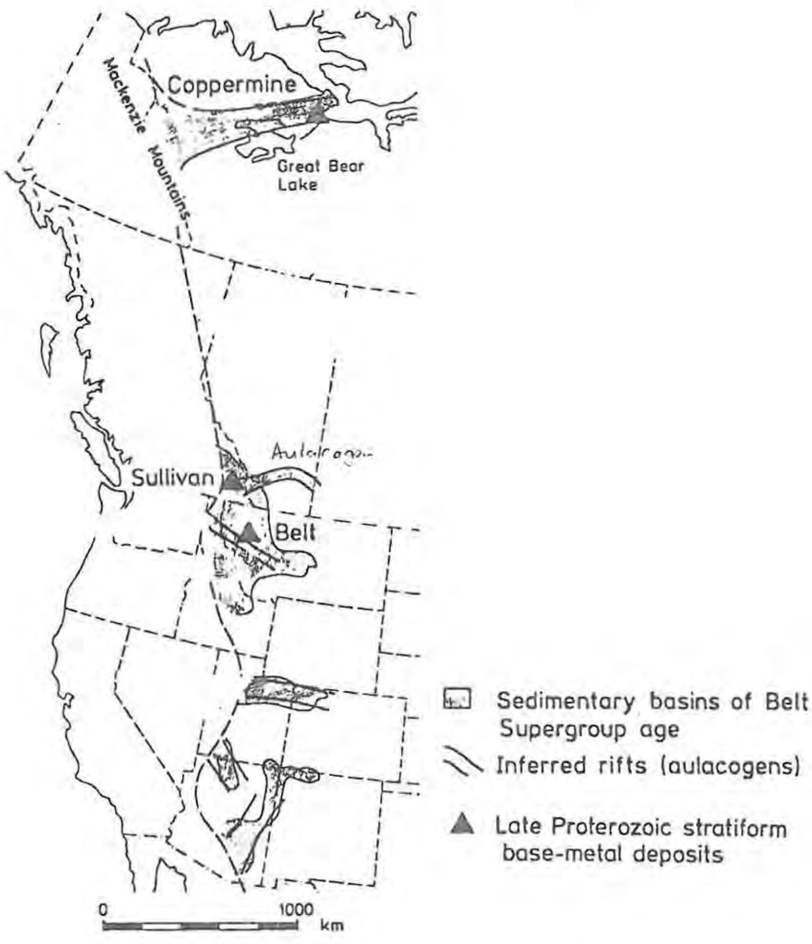


FIGURE 88: The regional setting of the Mid-Proterozoic Sullivan Lead-Zinc Deposit, British Columbia, Canada.

The Lower Purcell Supergroup quartzites and dolomitic argillites were deposited in prograding deltaic and tidal flat environments that developed on the western margin of the North American Craton. The overlying 6500m thick Aldridge Formation consists of alternating coarse-grained and fine-grained greywackes that were deposited by turbidity currents on a submarine fan complex (Thompson and Panteleyev, 1976). These were subsequently buried by sediments deposited on an advancing delta front. The only magmatic activity during the deposition of the Purcell Supergroup is represented by the extrusion of minor andesitic volcanics some 7000m above the Sulivan ore zone and by the intrusion of a series of stacked gabbro and hornblende-diorite sills (1200-1400my) that make up almost half the thickness of the Aldridge Formation (Ethier, et al, 1976). The Moyie Intrusions, developed within the confines of the aulacogen to the east possibly were intruded at the same time (Kanasewich, 1968).

Tectonic reactivation during the deposition of the Aldridge Formation initiated the formation of an intra-formational conglomerate, composed essentially of lithified underlying sediments, which was deposited in steep-sided irregular, probably erosional, depressions (Ethier, et al, 1976). This sequence of events suggests that the tectonic reactivation caused normal faulting which was followed by erosion and the deposition of debris flow conglomerates in erosional channels that are characteristic of the proximal facies on a submarine fan. The conglomerates are locally overlain by thin finely laminated carbonaceous argillites, which host of the Sulivan ore body.

The deposition of the laminated pyrrhotite-rich lead-zinc ore was accompanied by several episodes of footwall brecciation. The footwall mega-breccia and associated alteration zones are in general restricted to the western side of the ore body adjacent to the Sulivan Fault (Fig. 89). A roughly concentric lateral and a vertical mineralogical zonation is developed in the ore body. Massive pyrrhotite is preferentially developed on the western side of the ore body and grades upwards and outwards into finely banded galena and sphalerite-rich ore and then into predominantly sphalerite-rich ore on the fringes (Ethier, et al, 1976). To the east the mineralization passes gradually outwards into an iron sulphide-rich zone that persists laterally for up to 3000m. Individual sulphide bands in the laminated ore are laterally continuous for up to 1000m (Thompson and Panteleyev, 1976).

The Sulivan ore body was deposited during a tectonically quiesent period that immediately followed the tectonic reactivation which initiated the elevation of fault-blocks and erosion of intra-basinal sediments. The hydrothermal activity that led to the formation of the ore deposit was localized by the intersection of two major faults. The hydrothermal activity and associated footwall brecciation appear to have been controlled mainly by the Sulivan Fault zone. The Hellroaring Creek granodiorite stock (1265my) intrudes both the Aldridge Formation and Moyie gabbro sills near the Sulivan Mine and therefore post-dates the formation of the ore body. The presence of a calc-alkaline stock, which represents the diapiric rise of a confined calc-alkaline magma, possibly during the same period of magmatic activity as the extrusion of the minor andesitic volcanics in the upper part of the Purcell Supergroup. The presence of calc-alkaline hornblende-diorite sills within the dominantly tholeiitic Moyie Gabbros also indicates that the tholeiitic magmas were in part

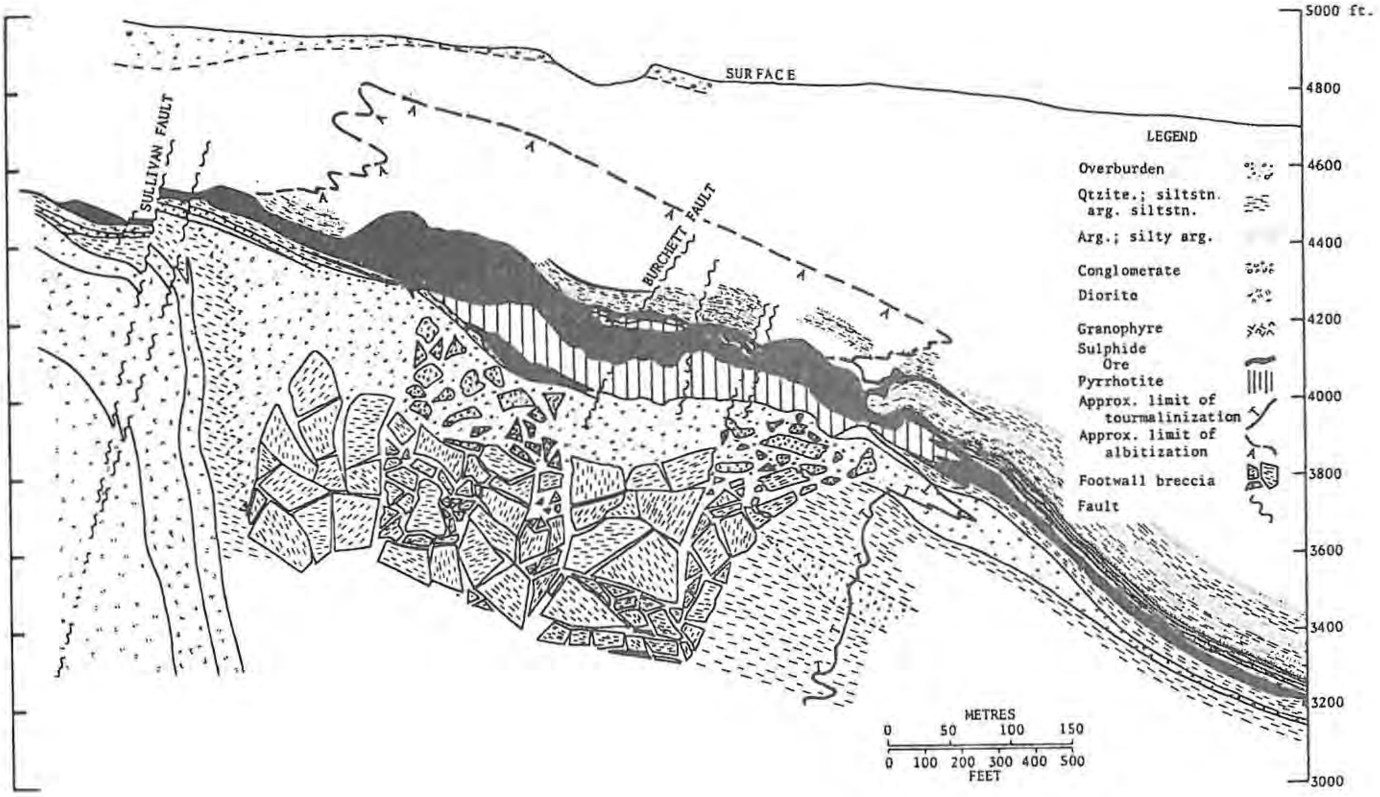


FIGURE 89: Cross-section of the Sullivan Lead-Zinc Ore Deposit, showing the development of the footwall breccia zone and conformable massive sulphide lens that grades laterally into sulphide-rich argillite (from Thompson and Panteleyev, 1976).

confined and that they assimilated minor amounts of sialic material during ascent. Such confined calc-alkaline diapirs in the early stages of magmatic activity could easily have been the source of the hydrothermal metalliferous brines that led to the formation of the Sulivan ore deposit, even though no volcanism is directly associated with the ore deposit.

VOLCANO-SEDIMENTARY ORE DEPOSITS IN MIOGEOSYNCLINES

The Irish Base Metal Deposits

A major proportion of the Lower Carboniferous lead-zinc ore deposits in Ireland are localized by major north-easterly trending normal faults. Most of the ore deposits including Tynagh, Navan, Gortdrum and Silvermines are hosted by Lower Carboniferous Limestones, although epigenetic vein-type mineralization occurs in older rocks (Fig. 90).

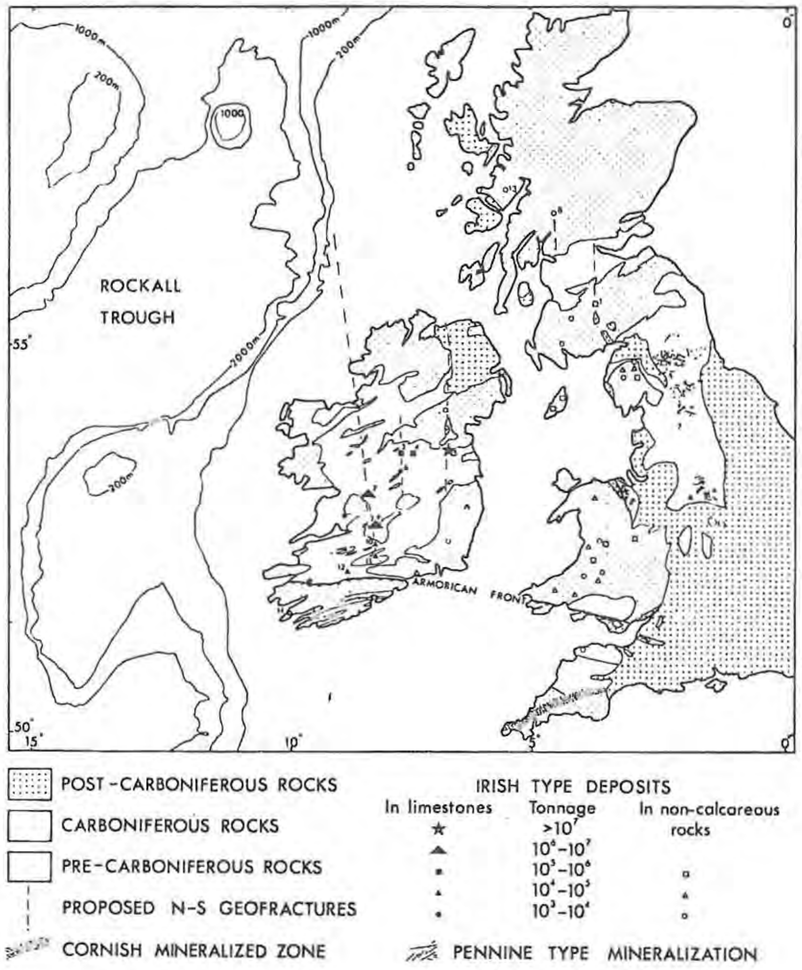


FIGURE 90: Regional setting of the Irish Base Metal Deposits. Associated epigenetic deposits are present in older rocks, particularly in Britian. Postulated geofractures show a marked parallelism to the Rockall Trough boundary (from Russell, 1976).

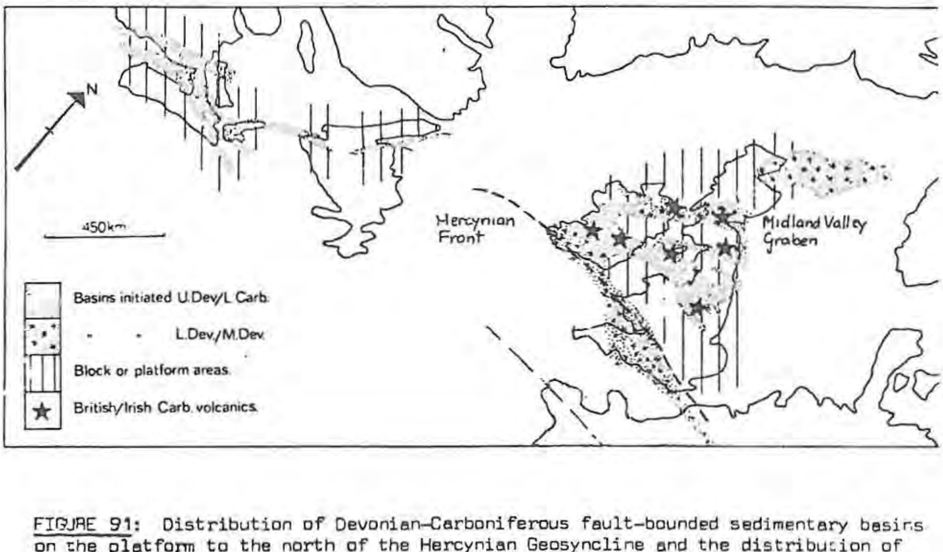


FIGURE 91: Distribution of Devonian-Carboniferous fault-bounded sedimentary basins on the platform to the north of the Hercynian Geosyncline and the distribution of Carboniferous volcanic centres (from Leeder, 1976).

The earliest rift-bounded basins were initiated in the Early Devonian in the south of England. These grabens were filled with locally derived coarse-grained continental sandstones (Whittaker, 1975). Normal faulting and associated continental clastic sedimentation in mainly half grabens did not extend onto the platform area to the north until the Late Devonian (Fig. 91). The gently dipping Lower Carboniferous sediments rest comfortably on unmetamorphosed Devonian continental clastics in the south, but further north are separated by a marked unconformity (Morrissey, et al, 1971). The deposition of the continental red beds were controlled by major fault scarps. These clastic sediments are best preserved in the NE striking 50-80km wide Midland Valley Graben which extends from Scotland into Northern Ireland (Fig. 91). In certain areas alkali and tholeiitic volcanism accompanied sedimentation. The clastic sediments were initially deposited on alluvial fans and later on prograding deltas. In response to a decrease in tectonic activity and dimished clastic influx a sequence of carbonates up to 1000m thick were deposited in tidal flat and shallow marine environments during a major marine transgression from the south to the north in response to gradual subsidence. The diachronous carbonates consist of a lower sequence of shaley and sandy lagoonal limestones that grade laterally into reef limestones which in turn pass laterally into dark graphitic basinal limestones. The reef limestones appear to fringe basement ridges with the basinal limestones developed further away (Derry, Clark and Gillatt, 1965). In the lower units the three dominant facies pass laterally into each other but eventually with continued subsidence the basinal shalely limestones covered a large part of the reef limestones and resulted in the formation of a thick sequence of basinal limestone.

In response to further crustal extension and basin subsidence, the southern area developed into a deep eugeosynclinal trough which eventually became the site of intense deformation and metamorphism during the Hercynian Orogeny at the end of the Carboniferous. The Irish platform occurs to the north of the Hercynian Front, which marks the extent of deformation and metamorphism during the Hercynian Orogeny (±280my). This front also defines the transition from Devonian continental sandstones in the north to Devonian marine deposits in the South and in addition the front marks a similar change from Carboniferous paralic to marine sediments in the north, to predominantly deep basinal sediments. The Hercynian Front therefore remained an important tectonic feature during the development of the geosyncline and its subsequent collapse. The

Irish base metal deposits are therefore in a miogeosynclinal environment.

The dominant fault pattern is a series of north-easterly trending normal faults, that are commonly downfaulted to the north-east. These faults often bring lower Carboniferous carbonates in direct contact with the Devonian sandstones and the earlier basement rocks of Caledonian-age. Locally stratigraphic sections tend to be thicker to the north of these faults while individual formations tend to thin out as well as steepen in dip towards the faults. This suggests that faulting occured contemporaneously with the deposition of the sediments (Derry, Clark and Gillatt, 1965).

Lower Carboniferous volcanic centres are developed in some areas and there is a broad coincidence between major ore fields and Carboniferous volcanisity, although in only a few instances is there a direct association between volcanism and mineralization, notably at Strontian, Gortdrum, Tynagh and Silvermines (Fig. 90 and Fig. 92) (Russell, 1976). The most prominant volcanic centre is developed in the Pallas Hills where trachy-andesitic and trachytic lavas and tuffs with some alkali olivine basalt flows are interstratified with the basinal limestones. Locally thin tuff beds are interstratified with the carbonates (Derry, Clark and Gillatt, 1965). Minor stocks and dykes of basic to intermediate composition are spatially associated with the volcanic activity.

The lead-zinc mineralization is best developed in the Lower Carboniferous carbonates but is also found in the Devonian sandstones underlying the carbonates. Numerous epigenetic vein-type deposits are scattered throughout the area in rocks of various ages (Fig. 92). These mineral occurrances are often localized in brecciated zones along faults. Uneconomic lead and copper mineralization is also associated with the plugs in the Pallas Green volcanic centre (Evans, 1976). A number of minor red-bed copper deposits are also developed in the Lower Devonian sandstones and mudstones.

The Keel deposit consists predominantly of mineralized breccias and fracture fillings in the Devonian sandstones and conglomerates. The intensity of mineralization decreases away from the fault zones and grades lateraly into disseminated mineralization. The disseminated sulphides are confined to the matrix of conglomerates and the pore spaces in the sandstones indicating that the mineralization is epigenetic. Replacement

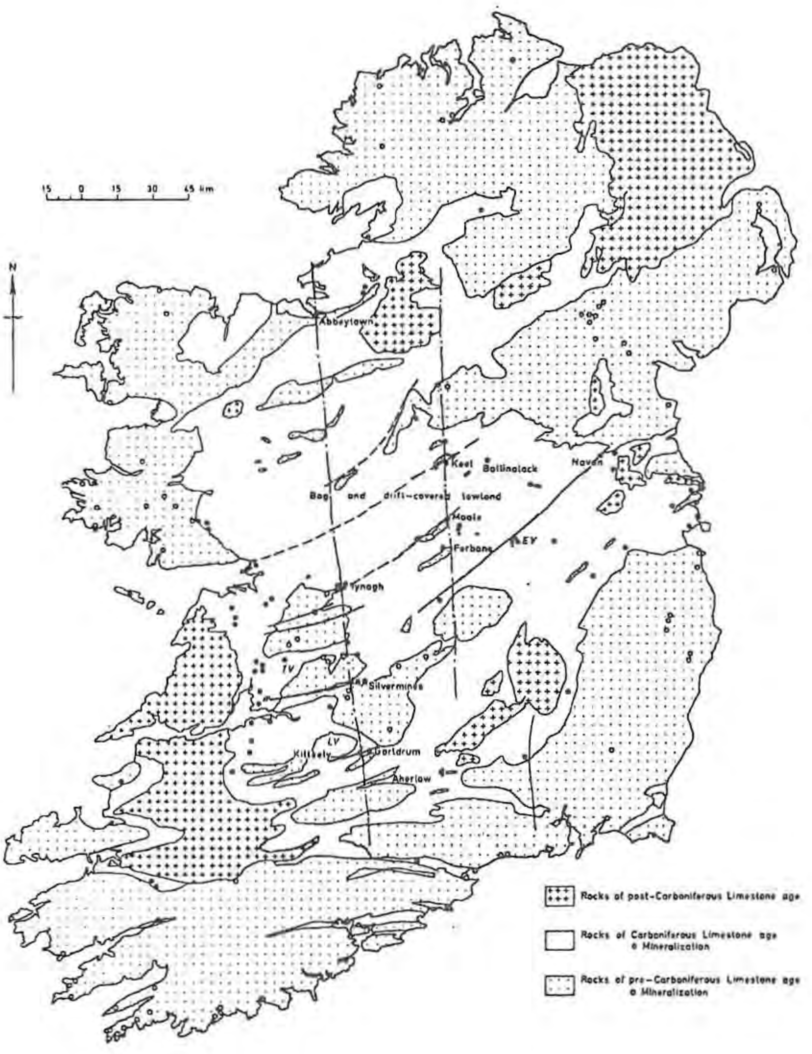
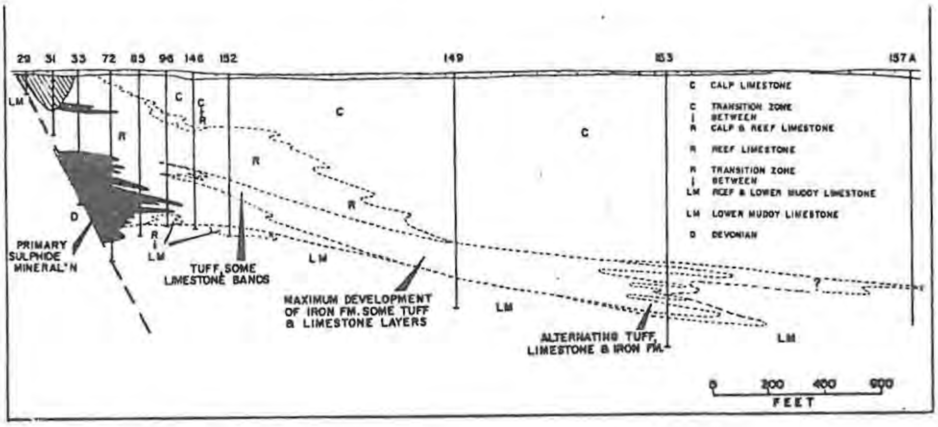


FIGURE 92: The distribution of lead-zinc-copper mineralization in Ireland (from Russell, 1976).

textures are also commonly observed in carbonate-hosted deposits. Dolomitization is the only important wall rock alteration adjacent to the Navan ore deposit. The alteration forms a halo that thickens and thins in sympathy with the ore body (Evans, 1976).

The upper G-Ore Zone at Silvermines is a fine-grained concordant stratiform deposit in contrast to the disconcordant coarser-grained fracture filling and replacement ore in the lower ore body. A large stratabound barite deposit occurs marginal to the upper ore body, which is also overlain by a thick chert horizon (Moressey, et al, 1971). The stratiform lead-zinc mineralization at Tynagh is localized by the intersection of the Tynagh Fault with the contact between the reef facies and basinal facies limestones. The ore deposit interfingers lateraly with a laminated green tuff which in turn interfingers with banded iron formation (Fig. 93). The banded iron formation appears to have been deposited in a restricted basin which was elongated parallel to the Tynagh Fault (Derry, et al, 1965). Thin banded iron formation lenses are also found within the reef facies limestones. The sulphide mineralization occurs as conformable layers and lenses, as well as in low-grade disseminated zones. Fine-grained galena and sphalerite are often found in alternating layers and bands in which colliform textures are common. Banded lenses are also developed in the more porous portions of the reef facies. The ore zones are developed as wedges that thicken towards the fault zone (Fig. 93). Copper tends to be concentrated in the lower parts of the main ore body adjacent to the main fault. Zinc shows a wider lateral distribution than lead and grades lateraly into pyritic banded iron formation. This in turn grades laterally into a hematitic chert. A syngenetic manganese halo extends for up to 7km away from the Tynagh ore deposit (Russell, 1976).



<u>FIGURE 93</u>: Cross-section through the Tynagh Ore Deposit showing the stratigraphic relationship of sulphide ore to tuff and banded iron formation (from Derry, et al, 1965).

The lead-zinc-rich and copper-rich mineralization both show a close spatial relationship with north-easterly trending faults. There also appears to be a strong northerly alignment of most of the deposits which led Russell to postulate the presence of north-south geofractures spaced at fairly regular 45-65km intervals. This is an important structural direction which controls to some extent the coastline of Ireland and also controlled the formation of Rockall Trough during the opening up of the North Atlantic in the Mesozoic (Fig. 90) (Russell, 1976). The presence of banded iron formation and chert as well as interbedded tuff horizons with some of the larger stratiform deposits indicate that the metals were derived from a magmatic source. In both the Tynagh and Silvermines ore deposits the depositional temperatures of the sulphides decrease away from the fault. The silver content of the galena in the Tynagh deposit also decreases away from the fault. These two features indicate that the stratiform sulphide deposits were formed by the deposition of the sulphides from metalliferous brines that were exhaled from the faults (Moressey, et al, 1971). The metal zonation, with high copper closest to the fault and lead, zinc and iron progressively away illustrate the different solubilities of the different metal complexes. Hematitic cherts were deposited under oxidizing conditions furthest away from the fault. The Lower Carboniferous Carbonates were deposited during a stable miosynclinal stage following the initial period of proto-basin formation. The limited volcanic activity associated with the carbonate deposition and differentiated nature of some of the volcanics suggests that the magmatism was confined below the platform. This enabled fractional crystallization to proceed and caused the development of metalliferous brines, which then preferentially migrated along the major fault zones. These solutions were either confined at depth to form structurally controlled vein-type deposits or were exhaled onto the sea floor as relatively low temperature brines where the metals were precipitated under reducing conditions to form stratiform volcano-sedimentary deposits. In most instances, however, replacement-type deposits developed in the carbonates due to reaction with the solutions. The replacement-type deposits are surrounded by low temperature alteration haloes, typically dolomitization (Moressey, et al, 1971).

STRATABOUND DEPOSITS IN CONTINENTAL YOKED-BASINS

The White Pine Copper Deposit

Mid-Proterozoic continental clastic sediments and associated sub-aerial tholeiitic volcanics, which accumulated in rift-bounded basins, are hosts to a number of important stratabound copper deposits on the North American Craton, of which the White Pine, Coppermine and Seal Lake deposits are the most important. The copper deposits are preferentially hosted by carbonaceous shale horizons developed above thick tholeiitic volcanic piles.

The 1400-1000my Seal Lake Group consists of a sequence of coarse-grained clastics and shales and tholeiitic basalts with intrusive gabbro sills, that reach a maximum thickness of 7000km. The Seal Lake Group is bounded on the east by the Pocket Knife Lake Fault which probably also controlled the distribution of the sub-aerial volcanism and sedimentation. Uneconomic native copper and copper sulphide occurrances occur within the basalts and associated grey shales. Economic copper sulphide mineralization is confined to the carbonaceous shales of the Adeline Island Formation, which directly overlies the lower tholeiitic volcanic sequence. The grey carbonaceous and reddish shales are interbedded with thin basaltic flows and hematitic quartzite units. The Adeline Island Formation is overlain by a thick sequence of coarse-grained continental clastics (Gandhi and Brown, 1975). The copper sulphides deposits are restricted to beds stratigraphically nearest to the underlying native copper bearing volcanics. Mineralogical studies indicate that the iron-rich sulphides are progressively replaced by copper-rich sulphides. A number of minor stratabound copper deposits are confined to reduced shales in the Belt and Purcell Supergroups (1450my-850my) on the west coast, of North America (Thompson and Panteleyev, 1976).

The White Pine Copper deposit occurs within the Keweenawan Rift System in the central part of the North American Craton. The rift is characterized by a series of 40-85km wide fault-bounded en-echelon segments separated by major cross fractures that were also active during sedimentation (Fig. 94). The continuation of the rift under Palaeozoic cover to the south is marked by a 1300km linear group of Bouguer gravity anomalies and associated magnetic anomalies (Chase and Glimer, 1973). The Keweenawan Rift is filled mainly by a 1600km thick succession of tholeiitic flood basalts, minor rhyolites and cogenetic intrusive gabbro sills, interbedded with continental sandstones and shales. The Duluth and Mellen Intrusive Complexes, which are contemporaneous with the extrusion of the older of the two lava sequences, were emplaced along the unconformity at the base of the Keweenawan Group (Sims, 1976). The Keweenawan Group consists of two separate volcanic sequences that are locally separated and overlain by continental sediments. The sediments occupy synclines developed over the basaltic flows along the axis of the rift and form thick sedimentary wedges on the flanks of the rift system. The White Pine copper deposit occurs on the south-eastern margin of the Keweenawan Rift adjacent to the White Pine Fault, a major north-westerly trending strike slip fault that transects the rift. The White Pine

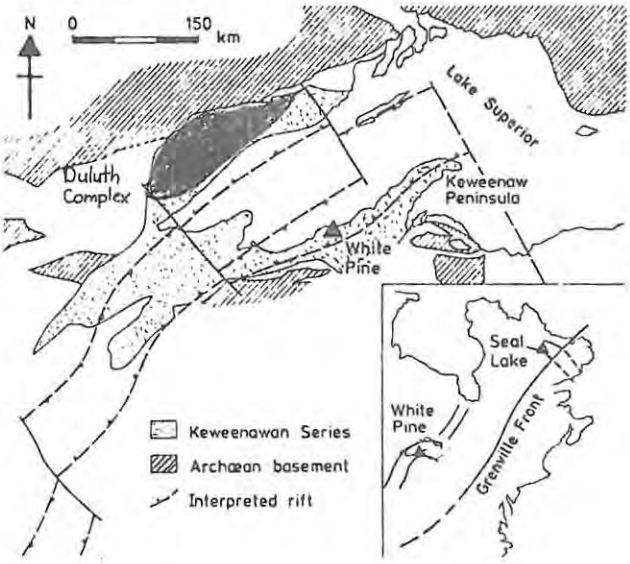


FIGURE 94: Regional setting of the Mid-Proterozoic White Pine Copper Deposit on the margin of the Keweenawan Rift (from Raybould, 1978).

copper deposit is hosted by the Nonesuch Shale which overlies the conglomerates. The deposit occurs a few kilometers to the east of a major rhyolitic volcanic pile (±1075my), which is up to 1200m thick and 24km across and formed a topographic high before and during the deposition of the coarse-grained clastic sediments (Gandhi and Brown, 1975). These coarse-grained clastic sediments also contain local lava flows up to 100m thick indicating the volcanic activity still continued, although at a much reduced rate, during deposition. Native copper deposits occur in amygdaloidal tops of lava flows and in conglomerate beds in the Keweenawan Peninsula. The Nonesuch Shale is a realtively thin, ±180m thick unit that extends up to 32km away from the mine until it interfingers to the east and west with reddish sandstones. Locally the shale lenses out onto paleo-topographic in the underlying sandstones (Fig. 95). The Nonesuch Shale consists of interbedded reddish, greenish and carbonaceous shales and siltstones that were probably deposited in a confined playa-lake environment.

Economic copper mineralization is confined to five stratigraphic horizons in the Nonesuch Shale (Fig. 96) (White and Wright, 1964). Although the copper mineralization is concentrated in specific carbonaceous horizons

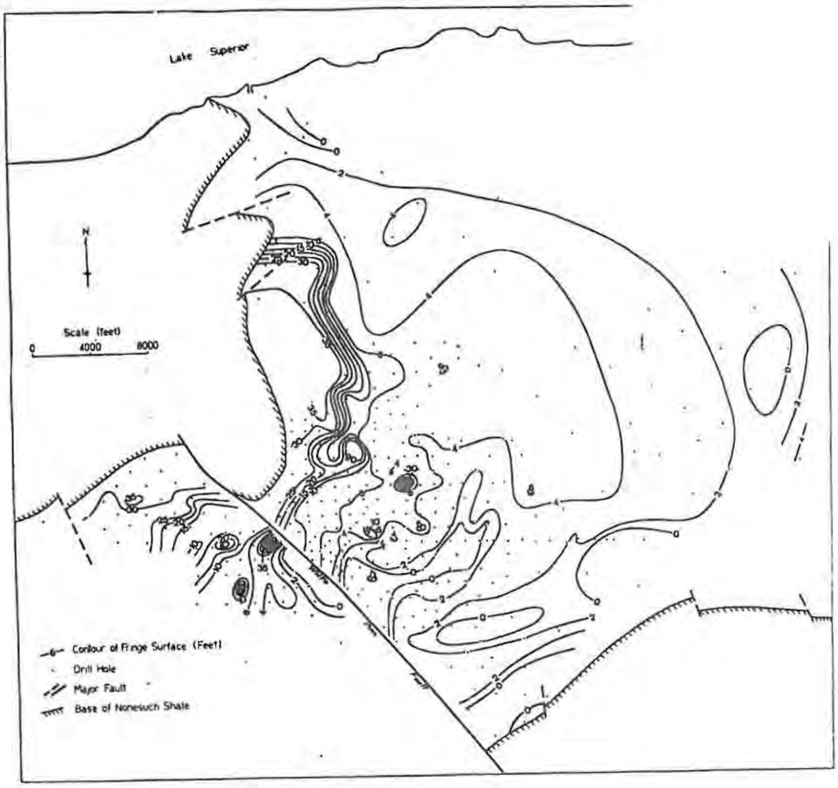


FIGURE 95: Contour map of the "fringe-surface" in the White Pine Mine illustrating the decrease in the height away from the intersection of the sandstone paleo-high with the White Pine Fault (from Brown, 1971).

the copper mineralogy shows a broad scale vertical and lateral zonation (Fig. 97). Native copper is concentrated in the underlying sandstones. This zone grades abruptly upwards into a chalcocite - native copper zone in the Nonesuch Shale followed by a chalcocite subzone that is in turn overlain by an extensive pyritic zone (Brown, 1979). The top of the cupriferous zone or "fringe-surface" is found to vary laterally across the ore deposit. This fringe-surface reaches a maximum height of 10m at the intersection of the White Pine Fault with a sandstone paleohigh and gradually decreases away (Fig. 95). There is a strong inverse relationship between the height of the "fringe-surface" and the concentration of copper in the mineralized zone (Brown, 1971). The copper grades also tend to decrease away from the White Pine Fault, suggesting that the fault acted as on aquifer for the mineralizing solutions. The copper in solution was preferentially precipitated in the reduced carbonaceous shales.

The major Mid-Proterozoic stratabound copper deposits are preferentially hosted by reduced carbonaceous shales that occur directly above major

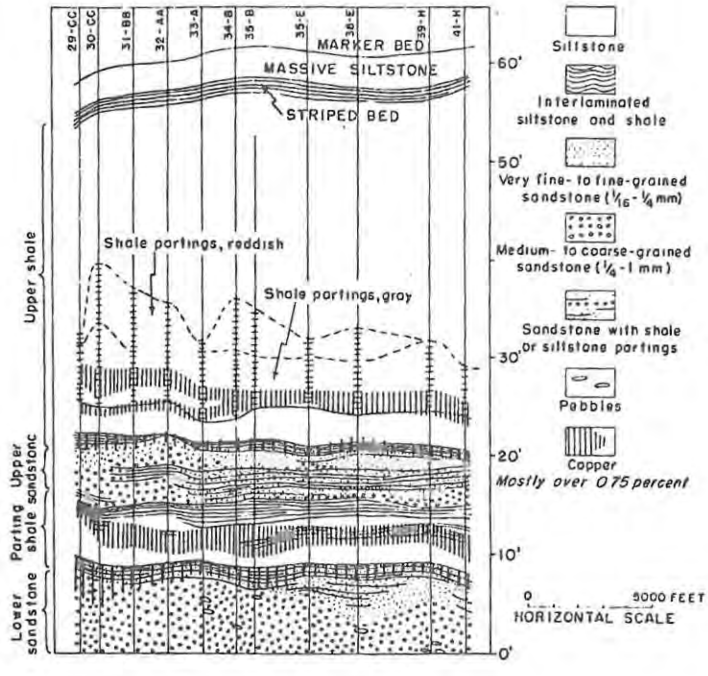


FIGURE 96: Stratigraphic cross-section of the White Pine Copper Deposit illustrating the concentration of copper mineralization in specific stratigraphic horizons (carbonaceous shales) (from White and Wright, 1964).

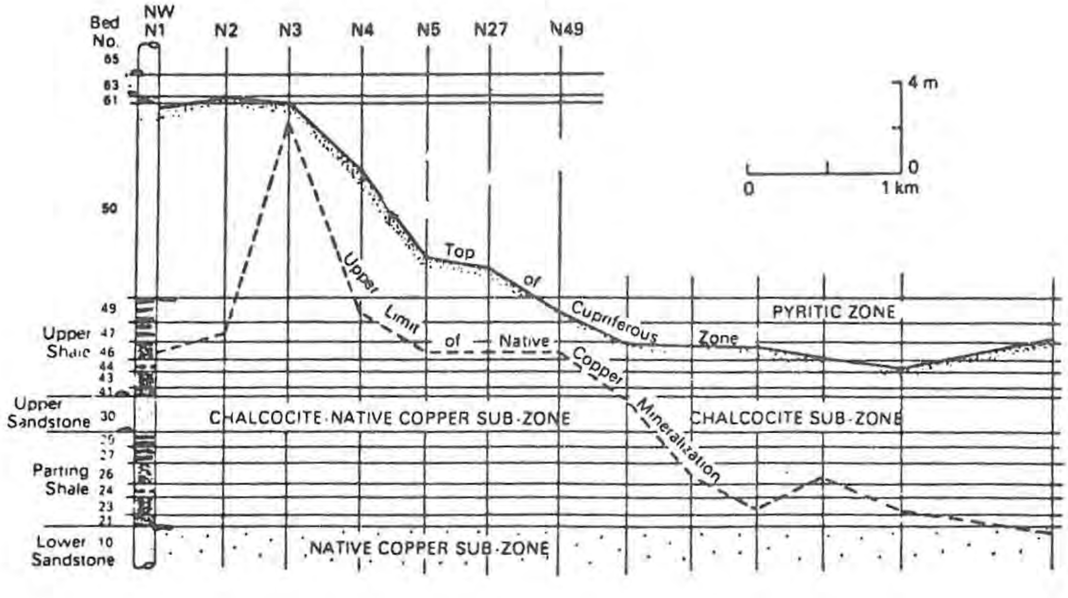


FIGURE 97: Diagram illustrating the transgressive nature of the mineralogical zonation pattern to the bedding of the Nonesuch Shale even though mineralization is concentrated in certain stratigraphic horizons. (from Brown, 1979).

tholeiitic volcanic sequence (Seal Lake) or are separated from the volcanics by coarse-grained continental sandstones (White Pine). Interbedded thin volcanic units illustrate that the volcanic activity continued contemporaneously with the sedimentation. The sediments and volcanics are confined to narrow rift-bounded grabens, which are also hosts for major differentiated mafic plutonic complexes. The ±1200my Duluth Complex occurs within the Keweenawan Rift in the vicinity of the White Pine deposit, which illustrates that the area was a zone of increased magmatic activity. The ±1200my Muskox Intrusion occurs in the vicinity of the Coppermine copper deposits in North-West Canada, while thick gabbro sills occur within the volcanic pile underlying the Seal Lake copper occurrances. The White Pine deposit has an almost direct spatial association with a major rhyolitic volcanic centre. This suggests the mineralizing solutions were derived by magmatic differentiation and then migrated up the permeable White Pine Fault. Reduced carbonaceous shale horizons, conditioned during sedimentation, acted as preferential hosts for the copper sulphide deposits. The mineralization at White Pine has a similar tectonic setting as Besshi-type volcanogenic deposits in that they are associated with bimodal tholeiitic basalt-rhyolite volcanism and the mineralization is directly associated with the rhyolitic volcanics. In the continental setting the magmatic metalliferous brines do not form stable brine plumes in response to temperature and density differences between the brines and sea water, but rather permeate porous sedimentary horizons. The metals in the brines are preferentially precipitated by reduced carbonaceous horizons, which illustrates that ore deposits are localized by the conditioning of the sediments during deposition. As a result the ore deposits have an apparent direct relationship with the sediments and not with the volcanics as in the case with the volcanogenic deposits. It would appear that sediment-hosted stratabound copper deposits developed in rift-bounded basins during tectonic conditions that allowed differentiation of tholeiitic magmas to form siliceous rhyolites and associated metalliferous brines.

The Zambian Copperbelt

Stratiform copper deposits are well developed in Late Proterozoic (1000-900my) platform sediments in Africa and South America. Most of the deposits occur in the basin margins adjacent to Archean Cratonic nuclei (Jacobsen, 1975). The initial stages of basin development are characterized by deposition of coarse-grained continental red-bed clastic sediments in local rift-controlled basins. This early stage of sedimentation and associated volcanisity marked the beginning of the Pan-African Orogenic Cycle that closely followed the extensive ±1000my Grenville-age Orogenic Cycle. The initial continental sedimentation in small proto-basins was followed by stabilization of the platform, slow subsidence and the deposition of thick carbonate shelf sequences.

The most important copper deposits formed during this period occur in the 190km Zambian Copperbelt. The mineralization is confined to the Lower Roan Group (Fig. 98) (Darnley, 1960). The Lower Roan Group, which reaches a maximum thickness of 1100m, was deposited on a irregular basement paleo-topography that had vertical differences generally of the order of 300m, but reaching up to 1000m (Mendelson, 1961). The paleo-topography exerted considerable influence on the distribution of the sediments. Sedimentation was confined to two, probably rift-bounded, troughs on either side of the Kafue Anticline. The Kafue Anticline, which was a structural high during sedimentation, is probably a structural manifestation of an original host block. The basement valleys which extend into the Kafue Anticline were filled by locally derived boulder beds and coarse-grained clastic sediments deposited on

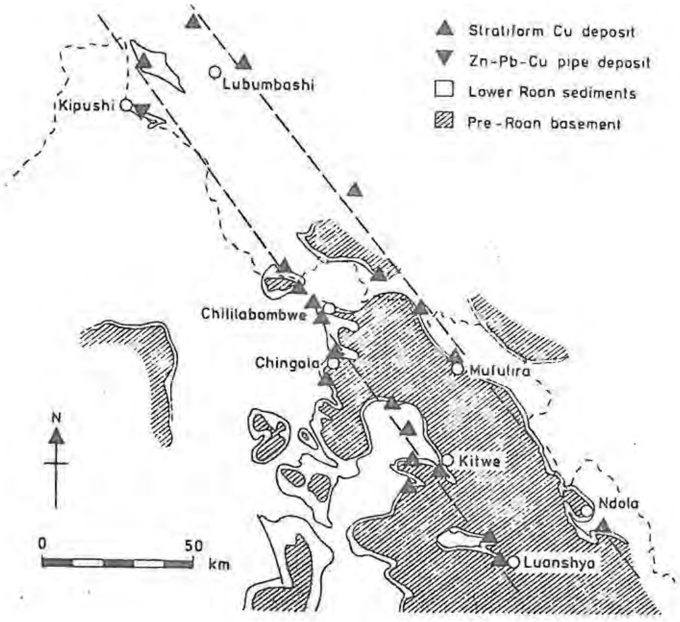


FIGURE 98: The regional distribution of the Late Proterozoic stratiform copper deposits in the Zambian Copperbelt with particular emphasis on the dual linearity of the distribution on either side of the Kafue Anticline (from Raybould, 1978).

alluvial fans. Local unconformaties and slumping adjacent to the basement highs suggests periodic reactivation of the boundary faults. The coarse-grained red-bed sandstones grade upwards into poorly sorted carbonaceous siltstones and sandstones with lenticular gypsum deposits. These clastic sediments have bimodal paleo-currents and contain evidence of periodic exposure suggesting that they were deposited in a tidal flat environment.

The Ore Shale is confined to the western side of the Kafue Anticline. Locally the Ore Shale lenses out along strike into thick stramatolitic bioherms that preferentially developed on basement highs. The Ore Shale grades upwards into the overlying dolomites of the Upper Roan Group. Sedimentation to the east of the Kafue Anticline is characterized by three repetitive cycles of coarse-grained clastics to fine-grained argillaceous sandstones with significant carbon contents. Although the sediments are identical in nature to those to the west of the Kafue Anticline, they cannot be correlated across the anticline suggesting that sedimentation was confined to small proto-basins (Mendelson, 1961). The reptitive cycles to the east indicate periodic reactivation of the adjacent source areas. This proto-basin was probably not sufficiently stable for any length of time to enable deposition of the equivalent of the Ore Shales at the end of each sedimentary cycle. The clastic sediments to the east are abruptly overlain by dolomites and shales of the Upper Roan Group suggesting that the depositional basin broadened with the onset of the deposition of extensive carbonates on a stable platform or miogeosynclinal environment.

There is some evidence of magmatic activity during the deposition of the Lower Roan. A significant number of scapolitized gabbro sills are intrusive into the sediments above the Chibuluma ore body while thin possible amygdaloidal lamprophyres occur at Ndola East (Darnley, 1960). It is possible that the Ore Shale itself is in part tuffaceous as it is overlain by some quite definite tuffaceous units (R. Mason,pers com). Volcaniclastic sediments are associated with the Shituru deposit of Zaire (Raybould, 1978). Outside the Copperbelt in the Mumbwa district there is also evidence of contemporaneous igneous activity by the development of quartz-syenite and quart-orthoclase porphyry plugs which show a strong enrichment in boron and copper (Darnley, 1960). At the present, sulphurous thermal springs within and near some of the mines are evidence of continued geothermal activity (Darnley, 1960), possibly along the original faults that controlled basin development and which are no longer recognizable due to the subsequent deformation. The major ore bodies in the Zambian Copperbelt are concentrated along two linear zones either side of the Kafue Anticline (Fig. 98). The copper mineralization is preferentially hosted by certain stratigraphic horizons, although in detail the copper mineralization transgresses the bedding (Fig. 99). To the west of the Kafue Anticline the ore bodies are preferentially hosted by the Ore Shale. The mineralization is particularly high-grade on the lower contact of the shale and decreases in grade upwards. The shale-hosted ore bodies are more elongate than the arenite-hosted ore bodies east of the Kafue Anticline at the Mufulira Mine. The copper sulphides in the arenite-hosted ore bodies occur intersitial to the coarser-grained detrital quartz and feldspar grains. In the high-grade ore zones the detrital feldspars are completely altered to sericite (Darnley, 1960). Tourmaline (up to 4,5%) and scapolite are typically associated with the copper mineralization. In the pyritic fringes of the ore zones albite is commonly found replacing detrital K-feldspar grains. Alteration is often concentrated in channels beneath the Ore Shale horizon suggesting that the mineralizing solutions travelled horizontally below the more impervious shales. Petrographic evidence indicates that the Lower Roan sediments underwent considerable alteration with the introduction of Mg, CO_2, Na, B and Cu prior to low-grade regional metamorphism (Darnley, 1960). The overlying dolomites are often siliceous with irregular replacement cherts and manganese-wad replacement deposits.

Minor contemporaneous magmatic activity, and the likelihood that some of the sediments in the Lower Roan are tuffaceous, suggests that metalliferous brines were of magmatic origin. The major ore deposits are concentrated along two linear zones, defined only by the distribution of the deposits themselves (Fig. 98). No structural features have been observed, although some distance to the south-east of the Copperbelt there is a north-west south-east trending shear zone in the basement with a vertical displacement of greater than 2500m (Raybould, 1978 and Darnley, 1960). On the western side of the Kafue Anticline the ore bodies are developed at the intersection of the linear with the Ore Shale. It is probable that the hydrothermal solutions migrated up the boundary faults and reacted with, and altered the sediments and preferentially precipitated copper in the reduced carbonaceous shales and arenites.

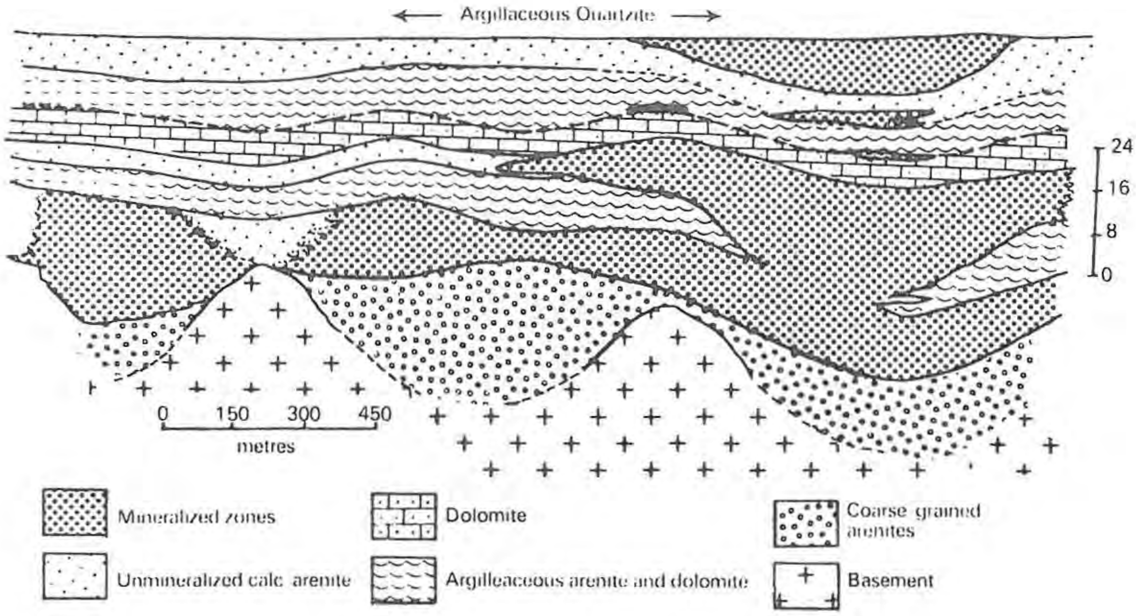


FIGURE 99: Idealised stratigraphic sequence of the Mufulira area, Zambia illustrating the preferentially mineralised arenites and the development of "barren zones" in the more constricted zones above paleo-hills (Jacobsen, 1975).

The Boleo Copper Deposits

The Pliocene Boleo stratabound copper deposits are hosted by a volcano-sedimentary sequence adjacent to the Gulf of California. The Pliocene volcaniclastic sediments and tuffs were deposited on an extensive Miocene volcanic terrain. The Miocene volcanism was terminated by normal faulting and eastward tilting. Subsequent erosion led to the development of an irregular paleo-topography. The paleo-valleys were slowly invaded by the sea from the east during the development of the Proto Gulf of California in the Early Pliocene. Locally clastic sediments, impure limestones and thick gypsum beds were deposited in a confined shallow marine environment. The initial period of chemical sedimentation was derived from the west. Coarse-grained gravels and clastic sediments were deposited on braided alluvial fans within the paleo-valleys and graded laterally into shallow marine sediments to the east. Normal clastic sedimentation was interrupted at least five times by andestic to trachy-andestic volcanic activity. Initial ash fall tuffs are overlain by volcaniclastic sediments in response to the erosion and reworking of the adjacent ash covered paleo-landscape (Wilson and Rocha, 1955). This second period of periodic sub-aerial volcanic activity was probably related to the opening of the Gulf of California by sea-floor spreading which started approximately 4 my ago (Larson, et al, 1968).

The copper sulphide mineralization occurs in gently dipping thin tabular bodies confined to certain relatively impervious clayey tuff beds within the Boleo Formation (Fig. 100). The five main ore bodies are each underlain by a conglomerate or down dip equivalent tuffaceous sandstone to the east. The main ore deposits are clustered around the Gulfward side of the projecting basement hills. The grades of the ore zones gradually decrease downdip and eventually the zones become barren towards the Gulf of California. The mineralized area varies between half to three kilometers wide over a strike length of eleven kilometers. High-grade ore is commonly concentrated in elongate zones that are orientated downdip with lower-grade zones (Fig. 101). There appears to be a relationship between the intensity of mineralization of the ore bodies in the Boleo Formation and the proximity to faults. In a number of instances the ore horizon is mineralized on one side of the fault, typically downdip on the gulfward side, and poorly mineralized or barren on the other side. The pre-Boleo age faults affecting the Miocene volcanics commonly contain quartz veins and stockwork copper mineralization. Locally copper mineralization occurs as irregular replacement deposits or fracture fillings within the clastic sediments, limestones and gypsum horizons.

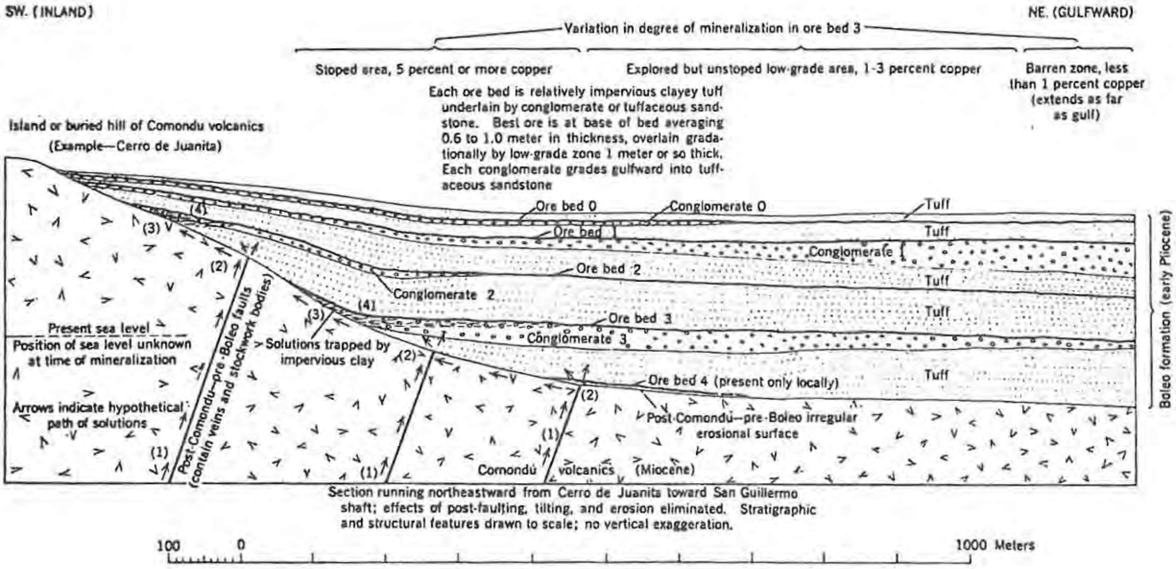


FIGURE 100: Typical cross-section through the Pliocene Boleo Copper Deposits illustrating the mineralization mechanism by ascending hydrothermal solutions that were preferentially trapped by the impervious clayey-tuff horizons (from Wilson and Rocha, 1955).

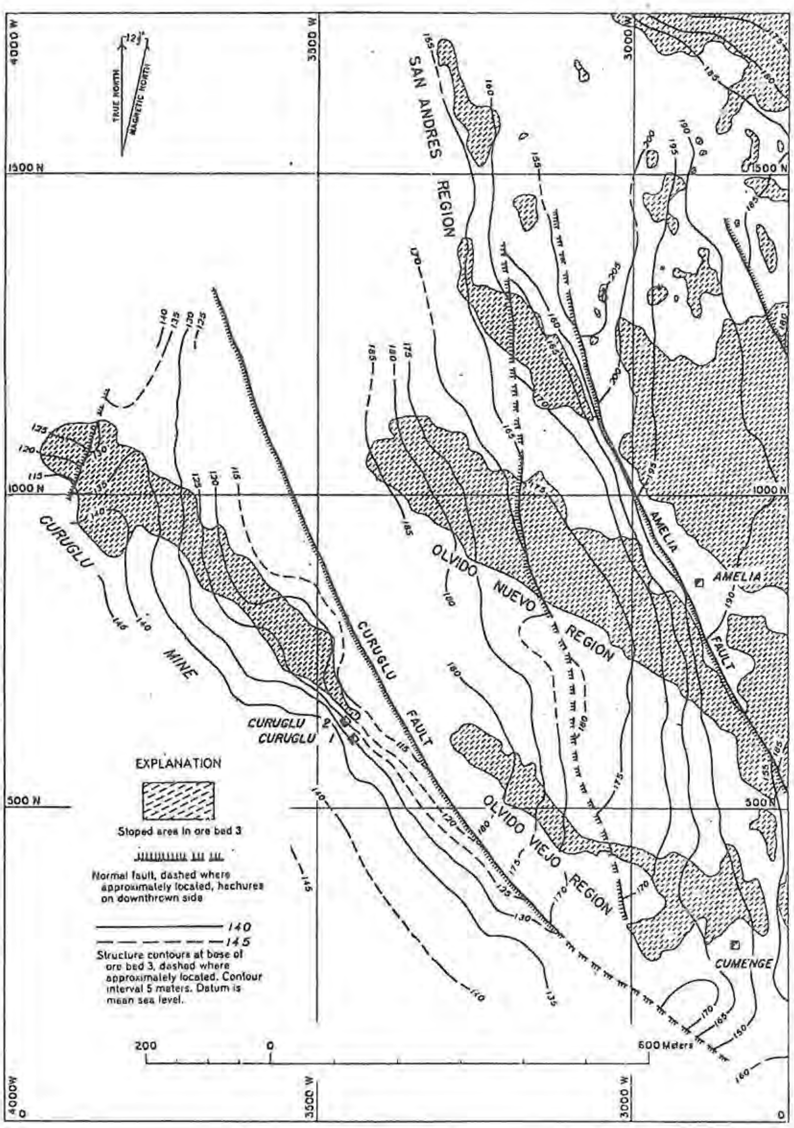


FIGURE 101: Diagram illustrating the distribution of ore shoots in the No. 3 ore bed and attitude of the ore horizon in the Amelia and Curuglu mines (from Wilson and Rocha, 1955).

The primary ore is a soft dark coloured clayey tuff with a high moisture content (25-30%) that contains mainly finely disseminated chalcocite. The main gangue minerals are montmorillionite with lesser iron and manganese oxides and minor amounts of gypsum, calcite and silica. In high-grade ores the alteration has generally proceeded to such an extent that the original texture of the tuff is destroyed. The mineralized zones contain significant halite contents with an average value of 2,2% NaCl (max. 6,4%). The lower contact of the ore zones at the base of the tuff horizon is typically sharp while the upper contact is graditional.

High zinc values occur in the hanging wall of the ore zones (Wilson and Rocha, 1955).

The stratabound copper mineralization is thought to have been derived from magmatic metalliferous brines which migrated along permeable major faults and fractures in the underlying Basement volcanics. The solutions spread out into the porous horizons in the Boleo Formation and were precipitated or impeded by the relatively impervious clayey tuff beds that overlie the porous conglomerates and sandstones (Fig. 100). The most effective traps occur where the clayey tuff horizons wedge out against the Basement paleo-hills and the trapped solutions were backed up against underneath the clay, and eventually deflected further down dip so that the grade of the ore gradually decreased down dip. Ore grade mineralization is not present in the porous coarse-clastic sediments and was preferentially precipitated in the tuff bands. Diffusion of the solutions through these preferential hosts caused the formation of a sharp contact of high grade ore on the base that gradually decreases upwards into low-grade zinc-rich pyritic sediments (Wilson and Rocha, 1955).

The mineralized area is small compared to the total extent of the tuff horizons and is confined to narrow elongate zones that are parallel to the basement paleo-valleys. It is significant that mineralization is commonly only developed in one of the five tuff bands, although the particular unit varies across the mineralized area, suggesting that copper present in metalliferous brines was preferentially partitioned into a particular host, depending on the proximity of that horizon to the feeder faults. The age of the mineralization occured some time after the deposition of the Boleo Formation and before the deposition of the Gloria Formation in the Middle Pliocene, as the overlying unconformity cross-cuts the mineralization (Wilson and Rocha, 1955).

Italian Pleistocene Uranium Deposits

In Central Italy, uranium mineralization associated with alkaline volcanism, is confined to small sediment-filled half grabens. These grabens were initiated in response to regional vertical uplift that was accompanied by rhyolitic and rhyodactic volcanism. At approximately 1 my alkaline volcanism began and overlaps the earlier felsic volcanism, active between 4 my and 0,6 my, in both time and space. The alkaline volcanics are mainly extensive pyroclastic flows, confined to very large rift-bounded depressions, which formed as a result of block faulting, horizontal extension and crustal thinning. Four separate major volcanic centres, each 50km across, outcrop continuously for 160km inside the major rift system (Fig. 102) (Locardi, 1977). Hotspring activity and CO_2 and H_2S emanations continue to the present day. The Italian Rift System shows all the characteristic features associated with mantle diapirism, early crustal doming, confined calc-alkaline volcanism and then alkaline volcanism in response to the development of penetrative rifts.

The uranium mineralization is more or less directly linked with the Pleistocene and Quaternary volcanism. The mineralization is preferentially hosted by the earlier Pliocene volcanosedimentary deposits which consist mainly of reworked volcanic sands, pumices and lacustrine deposits that thicken towards the walls of the rift. Low-grade pene-concordant uranium oxide deposits are disseminated in kaolinized and pyritized sediments. The attitude of the mineralization is not conformable to the bedding but rather follows a paleo-hydrostatic level (Locardi, 1977). The uranium mineralization is concentrated near transecting fault zones along the margins of the basin.

Economically significant fluorite deposits are interbedded with the most recent volcanosedimentary lacustrine deposits. These are syngenetic deposits which are associated with the latest phase of alkaline volcanism. Some lead, zinc, copper and mercury deposits are associated with the earlier felsic volcanic activity. The uranium deposits are associated with the Vulsini Volcanic Centre and have a close spatial relationship with native sulphur and pyrite deposits. Similar pyrite and native sulphur deposits are associated with the Sabatini Volcanic Centre to the south but no uranium deposits are known. This suggests that the uranium mineralization is directly associated with the volcanism in the Vulsini Volcanic Centre. The presence of stratiform fluorite deposits associated

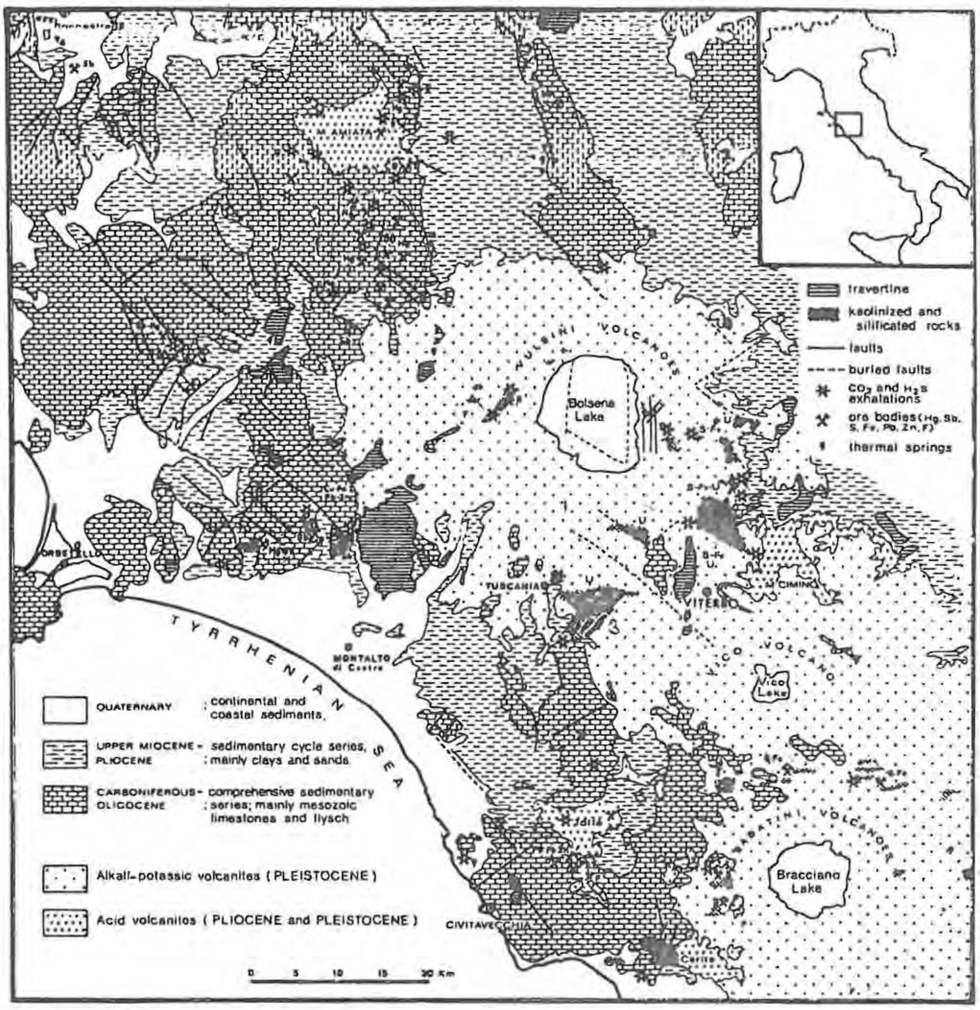


FIGURE 102: The distribution of Pliocene and Pleistocene felsic and alkaline volcanics, ore deposits, thermal springs and gas exhalations in the Central Italian Rift. Copper, lead, zinc and mercury deposits are associated with the Pliocene felsic volcanism, while uranium and fluorite deposits are associated with Pleistocene alkaline volcanism (from Locardi, 1977).

with recent lacustrine sediments suggests that the mineralization in the region is associated with magmatic hydrothermal brines that were derived by the sub-volcanic fractional crystallization of the alkaline magmas. Copper-lead and zinc are associated with the calc-alkaline volcanism while fluorite and uranium are associated with the differentiated alkaline volcanism. The uranium mineralization is probably only associated with the Vulsini Volcanic Centre due to more pronounced degree of fractional crystallization of the magma at depth. The presences of extensive alteration zones; kaolinization and silicification, also indicates that this centre has been an area of exhalative activity. Uranium is a geochemically mobile element and is readily redistributed by ground water movements so that it would most probably concentrate along a paleo-water table in unconsolidated porous sediments. Uranium mineralization has a close spatial relationship with hydrothermally altered areas and native sulphur-pyrite deposits. The uranium mineralization is also specifically associated with the Vulsini Volcanic Centre suggesting that its concentration is due to magmatic fractionation and that the mineralization is associated with magmatic metalliferous fluids.

The Athabasca Vein-type Uranium Deposits

The Canadian vein-type or unconformity-type uranium deposits show a definite spatial relationship to the Lower-Middle Proterozoic unconformity in both the Athabasca and older Beaverlodge Basins developed on the North-western Canadian Craton (Fig.103). Continental "red-bed" sedimentary deposits with similar lithologies, geometry and structural settings and age occupy intra-cratonic basins in widely separated parts of the north-western Candadian Craton. Most of these sedimentary deposits are intercalated with variable amounts of alkaline, tholeiitic and calc-alkaline volcanics. The isolated fault-bounded basins were filled by immature continental clastic sediments characterized by local angular unconformities. This cycle of proto-basin development was then followed by westward tilting of the craton, slow subsidence and the deposition of mature sandstones and shallow marine carbonates on an extensive stable platform in the Late Proterozoic. The sandstones and carbonates thicken to the west and contain increasingly more interbedded shales, and grade laterally into eugeosynclinal sediments deposited further to the west in a more rapidly subsiding trough (Fraser, et al, 1970).

The Athabasca basin was filled by 1600m sequence of cyclic fluvial sandstones that have no obvious large-scale lateral and vertical lithological variation, implying that basin subsidence and marginal basement uplift occured at a relatively constant rate.
Amygdaloidal basaltic to andesitic lava flows and gabbro sills occur only in the basal, coarse clastics of the older Martin in the Beaverlodge Basin just to the north of the Athabasca Lake area. Centripetal paleo-currents in the Athabasca Basin suggest that the preserved basin does not differ significantly from it's original extent. The lower sedimentary units have pronounced dips while the upper sediments are almost flat-lying and undeformed suggesting that deposition and deformation occured contemporaneously (Fraser, et al, 1970). Seismic refraction studies

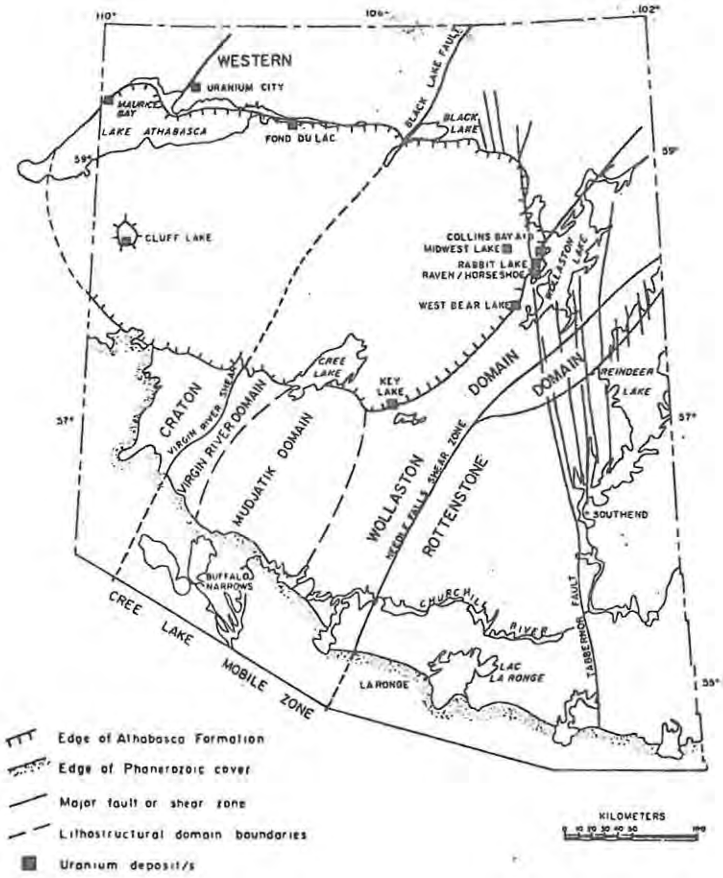


FIGURE 103: The structural setting of the Athabasca and Beaverlodge Basins, Saskatchewan, Canada, showing the distribution of vein-type or unconformity-type uranium deposits and in particular the dominant north-easterly structural grain of the basement (from Dabrowski, 1980).

suggest that the Athabasca Basin consists of a series of north-easterly trending basal depressions and swells which follows the trend of a number of major faults in the basement. These north-easterly trending faults also control the distribution of the older Martin Formation in the Beaverlodge area. Conglomerate lenses are best developed in the eastern part of the Athabasca Basin suggesting that this was the most active margin of the basin. It is significant that a number of the major uranium deposits are located close to this boundary (Fig. 103).

The uranium mineralization occurs in the Early Proterozoic metamorphosed sediments below the unconformity as well as within the sediments of the overlying Athabasca Formation. The host rocks are quite variable and include quartzo-felspathic gneisses, quartzites and graphitic horizons. The mineralization is commonly associated with chloritization, sericitization and kaolinization in shear zones and breccia zones. Structural control of the mineralization is important in all the deposits, with the mineralization being confined to fractures and breccias zones associated with major faults and shear zones.

Although a number of widely different theories have been put forward for the genesis of the vein-type uranium deposits it is considered that they could have had a similar origin to stratabound copper deposits. These uranium deposits occur in an identical tectono-sedimentary setting as the stratabound copper deposits which also developed during the same time period. Most, if not all of the uranium deposits are located within or adjacent to and elongated parallel to major faults. There appears to be a crude alignment of the east-north easterly fault that controls the Key Lake Deposit and the north-easterly trending fault through the group of deposits near Rabbit Lake (Fig.102). The mineralization is not confined to any specific host rock and is generally associated with wall rock alteration and the introduction of anomalous concentration of metals, notably nickel, cobalt, arsenic, copper, lead, zinc and gold. These high metal concentrations could have been derived from metalliferous fluids derived from magmatic sources. Some volcanism was associated with the deposition of the older Martin Formation but does not appear to be associated with the deposition of the more extensive Athabasca Formation. The absence of intense volcanism indicates that magmatic activity, which probably was associated with the initiation of the two basins, was confined. This would have led to the development of cauldron-type intrusive complexes and the late-stage development of magmatic hydrothermal fluids. Slow differentiation of the intrusive complexes is probably why the mineralization is of a significantly younger age than the host mineralization. The main period of mineralization in the Athabasca Basin occured at ±1100my, (Dabrowski, 1980) towards the end of the period of sedimentation that stretched from 1700my to 1200my, and was then followed by tectonically quiesent conditions and the deposition of extensive shallow marine sediments. The older mineralization in the Beaverlodge Uranium District was associated with deposition of the Martin Formation between 1830-1650my.

High uranium concentrations are often associated with highly differentiated derivatives of alkali basalt magmatism and also late-stage granitic liquids. The high nickel, gold and tellurium concentrations with some of the uranium deposits suggests that these fluids were probably derived from alkalic magmatism. Vein-type uranium deposits in France show a close spatial relationship with Hercynian Granites (Dabrowski, 1980). The hydrothermal fluids probably migrated along the major faults that controlled the development of the sedimentary deposits. Alteration associated with the mineralization, as well as some high temperatures recorded in fluid inclusions, suggest that the metals were precipitated directly from the hydrothermal fluids. The late-stage development of the fluids in relation to the sedimentation and possibly diagenetic reduction in the sandstone porosity is probably the main reason why most of the deposits are confined to the fault zones. As uranium is geochemically mobile, it is probable that some of the uranium was redistributed by ground water movement as was indicated for the Italian Pleistocene deposits. This is also probably a reason for the extreme variation in the ages of the uranium mineralization within a particular deposit.

Although the origin of the vein-type uranium mineralization is speculative these deposits have a common tectono-sedimentary setting with stratabound copper deposits. It is argued that while the stratiform copper deposits are generally associated with and closely follow tholeiitic flood basalt volcanism in continental rift-bounded basins, the uranium deposits are probably associated with continental sediments in basins that are associated with confined differentiated alkaline and granitic magmatism at depth. The metal association also suggests a higher degree of fractionation in the latter deposits. A lengthy period of magmatic differentiation possibly accounts for the larger time gap between sedimentation and mineralization in vein-type uranium deposits.

METAL DEPOSITS IN ACTIVE RIFTS

Metalliferous brines and Recent sediments have been discovered in a number of active rift systems. These are all associated with areas of Recent volcanic activity.

Sulphide deposits and exhalative metalliferous brines are known along the East Pacific Rise. The sulphide deposits are localized in a 1,5 km wide fault-bounded depression just off the active zone of extrusion of tholeiitic pillow lavas. Massive sulphides have built-up columnar orifices (hornitoes) that are commonly aligned parallel to structural trends (Francheteau, et al, 1979). The massive sulphide deposits were deposited from hot metalliferous brines in response to mixing with cold seawater. Direct parallels can be drawn between these deposits and

Cyprus-type cupreous-pyrite deposits associated with ophiolite complexes.

Metalliferous sediments and brines pools in the Red Sea are confined to fifteen known deeps along the axial trough of the Red Sea at depths ranging from 1350 to 2000 metres (Fig.104). The deep axial valley in the Red Sea has been formed by sea-floor spreading in the last 4 my, following arching and crustal thinning in the Miocene (Degens and Ross, 1976). The distribution of the metalliferous deposits are frequently associated with changes in direction of the median valley as a result of transform faulting. These transform faults are generally an extension of Precambrian fractures in the continental margins (Fig.104). The strong association between sites of brine discharge and transform faulting suggest that these faults may provide permeable zones for the migration of the brines. The Atlantis II Deep metalliferous sediments, which is the only deposit of economic interest known, contains 150-200 mill.tons of dry salt-free mud with an average metal content of 5% Zn and 1% Cu (Bignell, 1975). Some of the highest heat flows along the axial valley are centred on the Atlantis II Deep (Degens and Ross, 1976). The Atlantis II Deep brine pool was shown to be heating slowly over a 20 month period. However, the abnormally high heat flows characteristic of the region were insufficient to explain the observed temperature rise. The Red Sea metalliferous sediments consist predominantly of oxides, silicates and sulphides rich in iron and manganese with high zinc, copper, lead, cadmium and silver concentrations (Bignell, 1975). The associated brines have a metal association that cannot be derived from the evaporation of seawater. Sulphur isotopes studies have shown that the sulphur has a non-biogenic origin. Most of the evidence seems to be consistent with the derivation of the brines from mixing of brines of magmatic origin and normal seawater. A magmatic origin would also explain the observed temperature rise in the Atlantis II Deep Brine pool that cannot be explained by the abnormal geothermal gradient (Degens and Ross, 1969).

Metalliferous sediments occur in Lake Kivu on the East African Rift System. Lake Kivu is filled with minor sediments consisting mainly of reworked volcanic tuffs and soils. Lake Kivu contains stable salinity and temperature stratifications that are fed from below by saline hot springs. Dense hydrothermal brines are restricted to the deepest parts of the basin. Anomalous lead concentrations (up to 600ppm) are associated

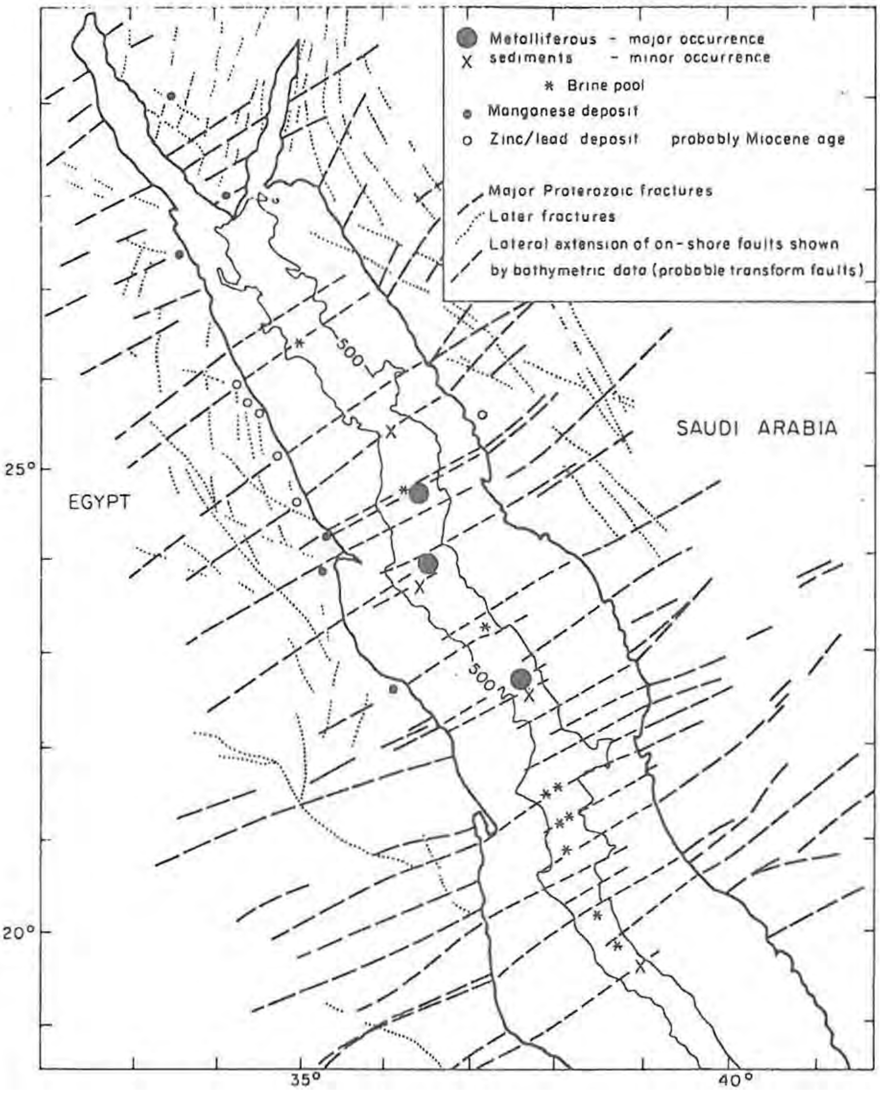


FIGURE 1C4: Distribution of metalliferous sediments and brine pools in the Red Sea in relation to continental fractures, presumed transform faults and on-shore Miocene deposits (from Windley, 1977).

with fairly recent sediments. The lead-rich zones are characteristically rich in organic carbon and also contain high molybdenum concentrations. The lead and molybdenum form organo-metallic complexes with the organic matter. Zinc is also present as chelated complexes in buoyant organic globules. These globules are less precipitous and as a result carried into the neighbouring Lake Tanzania, accounting for the high zinc content of all East African Rift sediments (Degens and Ross, 1976). The fluorine contents of the sediments vary between 0,1% and 0,6% F, and are particularly high in the lead-rich horizons. The metal distribution through a typical stratigraphic column illustrates the change in the metal abundances with time. The lead-rich sediments are associated with late-stage hydrothermal and volcanic activity after the main volcanic episode characterized by high Al_2O_3 and Mn metal contents in the stratigraphic column (Fig.105). The various heavy metals in the brines are enriched between 10 and 10,000 times the mean concentration of seawater, although the salinity is approximately a tenth of the salinity of seawater. Stable isotopes in the brines indicate that the hydrothermal system is charged by local rainwater (Degens and Ross, 1976). It has

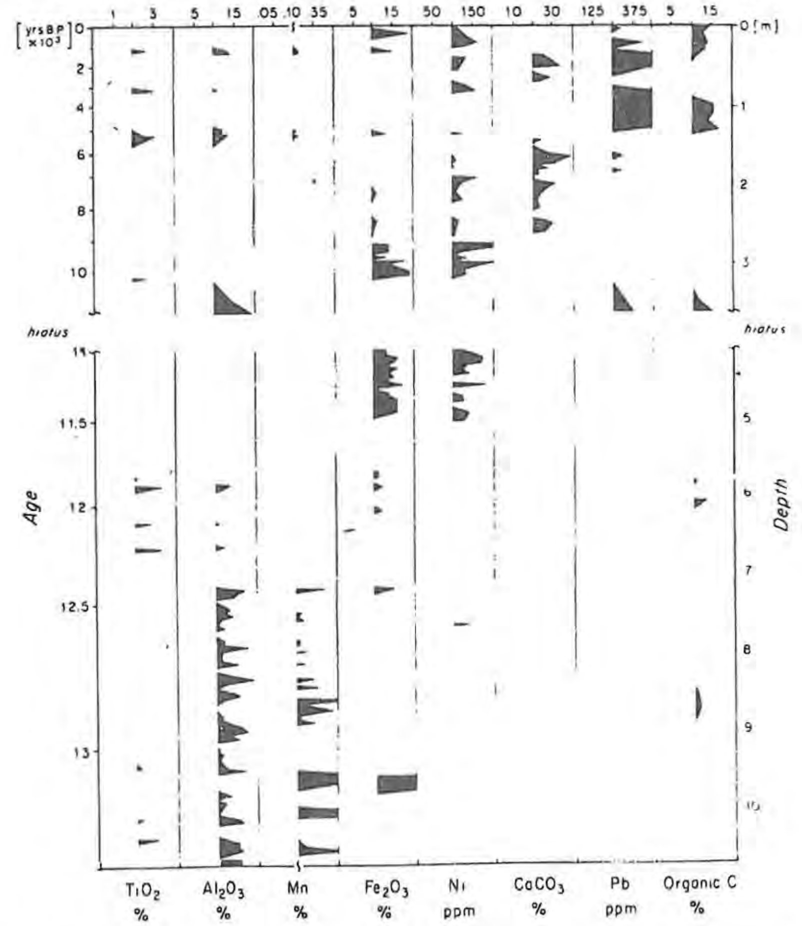


FIGURE 105: Chemical stratigraphy of sediments in Lake Kivu showing the progressive decrease in the tuffaceous component (high Al_2O_3 and Mn) and an increase in the hydrothermal component (high Pb) in the continental sediments with time. Note that the high lead peaks follow closely on isolated "tuffaceous" peaks suggesting that the metalliferous brines have a magmatic source (from Degens and Ross, 1976).

been suggested that the hydrothermal activity coincides with pluvial times but this does not account for the association of the high metal concentrations at the end of a volcanic episode (Fig. 105). It is probable that the metals were derived from a magmatic source and diluted by meteoric waters to form a low temperature dilute brine that is slowly discharged into the lake bottom. Metals are deposited by organo-metallic complexing under reducing conditions that exists below a depth of 50m to form uneconomic anomalous metal accumulations.

Geothermal brines are developed near the axis of the Salton Trough, a sediment-filled graben bounded by transform faults in the San Andreas Fault Zone. The Salton Sea Trough occurs on the extension of the Gulf of California which is an active zone of transform faulting and sea-floor spreading (Fig. 106) (Larson, et al, 1968). The felsic volcanic activity

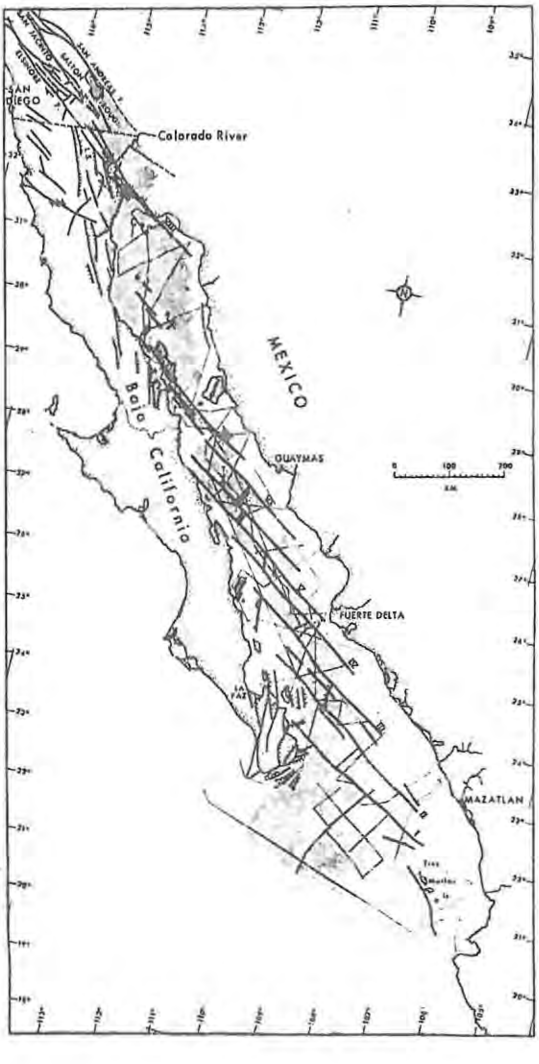


FIGURE 106: The structural setting of the Salton Sea as a transform-bounded pull-apart basin at the end of the Gulf of California, which is an active spreading centre (from Moore, 1973).

at Cerro Prieto and the Salton Sea is the surface manifestation of confined magmatic activity at depth, which with time, will probably develop into a zone extensive tholeiitic volcanism and eventual sea-floor spreading as Baja California moves progressively away from the Mexican mainland. The Salton Sea Trough is a narrow structural basin filled mainly with fine-grained deltaic sandstones and is at present the site of deposition of argillaceous sediments in a playa lake environment. The zone of maximum downwarp, centred on the Salton Sea, was also an area of Quaternary felsic volcanism and present-day anomalous heat flow and hotspring activity. The Quaternary volcanism is centred at the intersection of two major faults while the hotsprings are aligned parallel to one of the faults. Geothermal metalliferous brines are confined to porous sandstone units below an impervious shale capping that exists at 100m depth. Discharges from the surface hotsprings contain fifteen times less dissolved solids and no base metals and show a marked O^{18} shift compared to the geothermal brines which suggests that metalliferous brines at depth are in equilibrium with surface dilute meteroic pore waters, probably separated by a double diffusive thermal and salinity boundary (Helgeson, 1968). Isotope studies suggest that at least half the lead in the brines was acquired from the sediments (Doe, et al, 1966). The geothermal brines are enriched in iron, silica, manganese, lead, zinc, copper and silver. The brine is in equilibrium with greenschist metamorphic reactions at depth and is actively precipitating sulphides, chalcopyrite and sphalerite in the sandstone pore spaces (Muffler and White, 1969). The brines are poor in reduced sulphur. During production testing on the geothermal wells a siliceous scale, rich in iron, copper and silver, was deposited in the discharge pipes. It is significant that even though the brines contain significantly higher lead and zinc contents, only copper and iron sulphides and native silver were deposited in response to a decrease in temperature. If, however, the sulphur-poor brines present at depth were exhaled into a reduced sulphur-rich environment an ore body containing approximately 20 mill tons at 12% Zn, 2% Pb, 0,15% Cu and 200g/tAg, would be deposted (Skinner, et al, 1967).

THE ASSOCIATION BETWEEN RIFTS AND MINERALIZATION

Rifting of the earths crust and magmatism are a direct response to mantle advection. Since the development of rifts and the generation of magmas are related to the same geodynamic process, it follows that rifts will act as major conduits for the transfer of mantle and lower crustal derived magmas. The extent of the surface manifestation of the magmatism depends to a large extent on the state of stress in the crust and therefore the permeability of the rifts. Under confined conditions the mantle-derived basaltic magmas interact with the sialic crust and generate calc-alkaline magmas, while under tensional conditions the rift zones act as major channels for the transfer of primary basaltic magmas from the mantle to surface. In the early stages of mantle advection the crust is relatively brittle and as a result, caulder-type magma chambers would develop in the upper levels of the sialic crust. Magmatic differentiation under tectonically quiescent conditions would lead to good crystal-liquid separation and the concentration of the incompatible elements to such a degree that a metalliferous brine could be generated. Continued tectonic activity would lead to the disruption of fractional crystallization by periodic extrusion and pressure quenching of the magma and as a result poor liquid-crystal separation that would not lead to the generation of a hydrous phase. Therefore the structural setting of the magmatic activity is important to enable metalliferous brines to develop. These conditions would typically occur in stable platform settings and also during relatively minor periods of tectonic inactivity, usually at the end of a major volcanic cycle in more active troughs or eugeosynclinal settings.

Mantle-derived tholeiitic magmas form thick basaltic sequences during early stages of rifting and basin development in response to the extrusion along permeable rifts. Under relatively confined conditions, in the early stages of continental rifting, or incipient rifting in troughs, basaltic magmas would be sufficiently confined to produce bimodal basalt-rhyolite volcanic suites. This differentiation often results in the generation of typically copper-zinc-rich metalliferous brines. Fractional crystallization of confined hydrous calc-alkaline magmas would lead to the generation of metalliferous brines rich in copper, lead, zinc, silver and barium. The composition of the brines however, depends to a large extent on the nature of the sialic crust and the extent of interaction between basaltic magmas and the sialic crust.

The transfer of heat with limited interaction between basaltic magma and sialic crust could lead to the generation of anatectic felsic magmas enriched in uranium. The increase of radiogenic lead with time is thought to be the main reason why younger volcanogenic deposits contain significantly higher lead values and illustrates the effect of the interaction with the sialic crust has on the trace element characteristics of calc-alkaline magmas.

The permeability of the rifts determines the association between magmatism and the metalliferous brines. Highly permeable rift zones, particularly well developed on the margins of major troughs or eugeosynclines and in island arc settings result in a direct association between volcanism and the generation of volcanogenic ore deposits. Semi-permeable rifts, particularly those bounding major aulacogens, result in a limited surface expression of volcanism, generally as minor interbedded tuffs within a sedimentary pile that are commonly associated with stratiform volcanosedimentary ore deposits. Confined volcanism during initial crustal doming, rift initiation and the development of yoked-basins results in an often enigmatic relationship between ore deposits and volcanism. Stratabound copper deposits often show a close association with tholeiitic volcanism while uranium deposits generally have an indirect association with alkaline or felsic volcanism.

The mineral association in the different deposit types appears to be related to the distance between the origin of the brine and depositional site, which is in affect a function of the intensity of the volcanic activity. Volcanogenic deposits are the direct result of the interaction of hot dense brines with seawater which initiates the early precipitation of copper and later lead and zinc. As the source of the volcanism and brine becomes more removed the volcanic activity becomes significantly reduced and often the metals in the hydrothermal fluids become fractionated during their migration from the source to the depositary. A decrease in temperature would cause most of the copper to precipitate and as a result lead and zinc can be effectively separated from copper. This is often illustrated by the lateral zonation in some volcanosedimentary deposits where copper is deposited in a scinter-type setting adjacent to the exhalative centre, while lead and zinc are precipitated further away under reducing conditions in restricted basins to form stratiform bedded lead-zinc deposits. Epigenetic copper deposits in fault zones are often a result of early precipitation of copper from metalliferous brines and would result in the separation of lead and zinc from copper. The extent of separation of the different metals depends on the residence time of the brines in the major conduits and the associated change in temperature.

The conditioning of the depositional environment or the host sediments is often critical for the formation of deposits that do not show intimate relationships with thick volcanic piles. The presence of reducing conditions in the depositional environment appears to be a pre-requisite for the generation of stratiform volcanosedimentary ore deposits. The most important volcanosedimentary ore deposits are hosted by basinal carbonaceous shales, generally deposited on the distal facies of a submarine fan system within a trough or aulacogen,or are associated with reefal carbonates in a platform setting.

The relationship between sedimentation and brine activity is a critical factor in the formation of a volcanosedimentary ore deposit. Black-shale hosted lead-zinc ore deposits commonly occur as thin units within thick stratigraphic section of poorly mineralized sediments. This is a direct result of the rate of sedimentation. A high influx of volcaniclastic, epiclastic or shelf-carbonate detritus would result in a relatively thickly bedded sediments with scattered sulphide laminae that developed during quiesent periods and the formation of a thick poorly mineralized stratigraphic section. Volcanosedimentary ore deposits are confined to periods with a limited influx of detritus and the formation of thinly laminated carbonaceous shales. As a result tectonic quiesent periods are necessary to reduce the amount of clastic influx and allow the formation of volcanosedimentary deposits.

Porous zones in carbonate breccias zones in reef complexes are often important sites of syngenetic precipitation of lead and zinc, under reducing conditions associated with decaying algal matter. A few deposits in platform carbonates sequences show evidence of volcano-sedimentary association by the development of interbedded tuff and banded iron formation horizons in the ore zone.

The strong zonation between carbonate-hosted lead-zinc deposits in the miogeosyncline and the polymetallic volcanogenic and Cyprus-type deposits in the adjacent eugeosyncline of the Appalachian Geosyncline is striking (Fig. 81) and suggests that there is a tectonic control on the metal distribution. As the mantle diapir is at a greater distance below the stable miogeosyncline, associated magmation would most likely be confined to relatively deep-seated plutonic complexes along rifts. Should metalliferous brines be generated, copper would be effectively separated from these brines during their migration to surface along the rifts. The metals would then be preferentially precipitated in porous reef facies carbonates as epigenetic or replacement-type deposits in anoxigenic environments at the sediment-seawater interface to form carbonate-hosted volcanosedimentary deposits. In most cases the lead-zinc-rich brines would not reach surface but would intersect porous zones in the carbonates at depth. The metals would be preferentially deposited under reducing conditions in reefal zones as Mississippi Valley-type ore deposits.

The conditioning of the sediments is a critical factor in determining the preferential concentration of copper sulphide mineralization in a continental yoked-basinal setting. Stratabound copper deposits are hosted by reduced carbonaceous horizons deposited in a playa-lake or lagoonal environment. The mineralization generally occurs after any volcanic activity because the conditions during tholeiitic volcanism do not allow hydrothermal brines to develope. During the tectonic quiesent conditions after the main volcanic activity metalliferous brines could be developed and exhaled up along rifts. These brines would permeate the porous continental sediments and the metals would be preferentially precipitated in previously conditioned reduced horizons. The stratabound mineralization therefore has a character that is far removed from the associations in a volcanogenic deposit and is controlled more by the host sediments. The presence of extensive low-grade alteration zones and the introduction of anomalous trace element concentrations suggests that the mineralization is associated with magma-derived hydrothermal brines.

Uranium mineralization shows a very variable relationship with the host sediments and is often not associated with indications of volcanic activity. However, such an association would be expected if the uranium is derived from confined anatectic granitic magmas under high crustal stresses that did not enable rifts to penetrate to the mantle. Uranium derived from differentiated alkaline magmas would, however, have a spatial relationship with alkaline volcanism. Uranium mineralization is often associated with continental clastic sediments. The porosity of the continental sandstones would be particularly important in determining the geometry of the uranium deposits. The development of uraniferous brines early in the sedimentary history of a yoked-basin would probably allow the redistribution of the geochemically mobile uranium by ground water movements. The late-stage development of a metalliferous brine after diagenetic cementation of the sandstone would, however, confine the hydrothermal activity to the major faults. In the former situation peneconcordant and roll-front-type deposits would develop while in the later case the deposits would be typically vein-type or unconformity-type uranium deposits associated with alteration zones and anomalous metal associations.

Ore deposits develop during periods of tectonic inactivity at different times during the development of rift-bounded yoked-basins, aulacogens troughs and eugeosynclines. These periods of inactivity enable fractional crystallization of the magmas and the development of metalliferous brines. The metal associations depend to a large extent on the magma-type. The rifts act as major conduits for both magmatic activity and hydrothermal activity. The interaction of these brines at or close to the surface results in the formation of stratiform or stratabound ore deposits. Since rifts are the major conduits for the transfer of magmas and brines from depth these ore deposits will have a close association with major rifts.

As rifting, magmatism and basin development are controlled by the same geodynamic process major stratiform and stratabound ore deposits will have a definite tectonic zonation and will develop preferentially along major rifts.

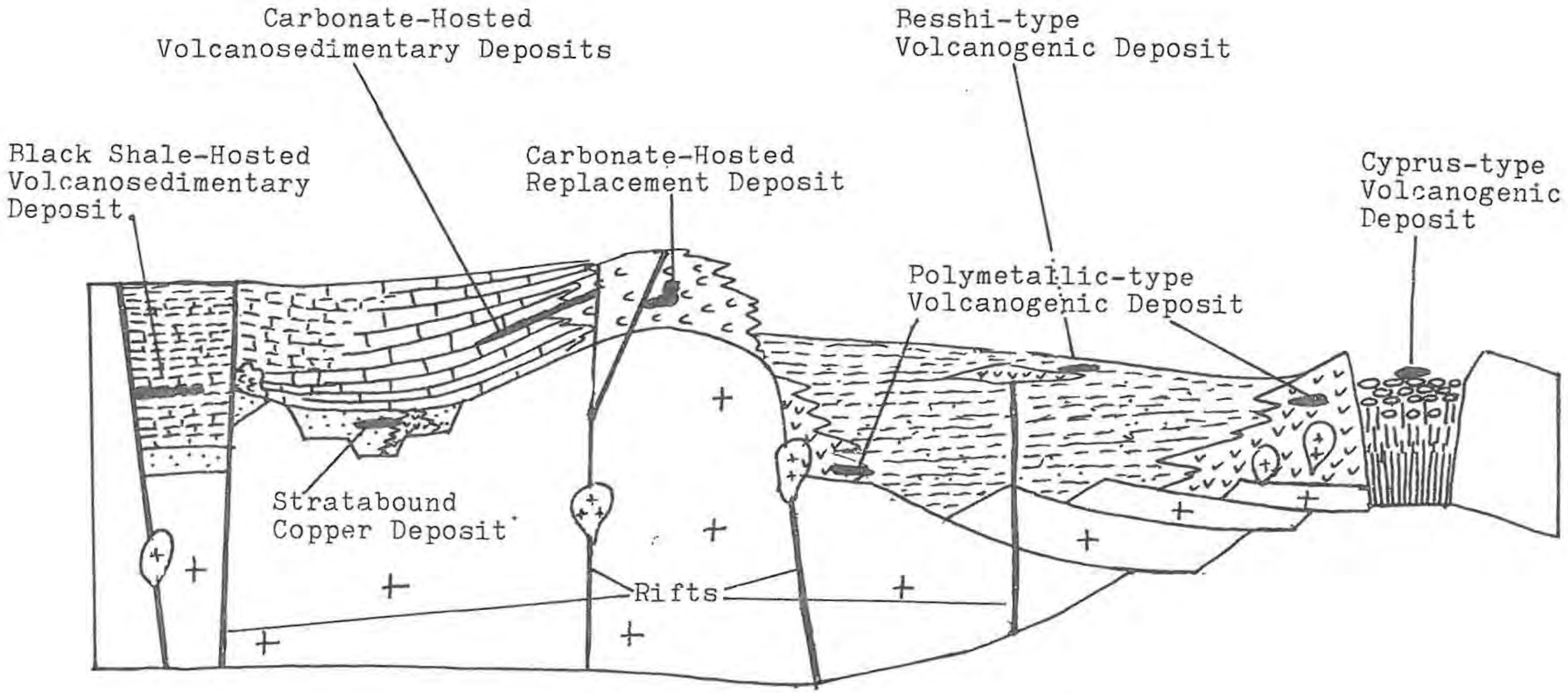


FIGURE 106: Structural Settings of Stratiform and Stratabound Ore Deposits.

ACKNOWLEDGEMENTS

I would like to thank the Base Metal Division of Anglo American Corporation of South Africa for giving me the opportunity to attend the M.Sc.Course at Rhodes University as it has been a stimulating and rewarding year.

I would like to thank Professor Bob Mason for his guidance and constant stimulation throughout the year and the Staff of the Geology Department at Rhodes University for their contribution to the development of the M.Sc. Course.

I am extremely grateful to Myra Frewen for typing this dissertation.

Most of all, I wish to thank my wife, Jacqui for her encouragement and moral support throughout a long year.

REFERENCE

Bahat, D. (1979). On The African Rift System: Theoretical And Experimental Study. Earth and Planet. Sci. Lett., 45, 445-452.

Baker, P.H., Mohr, P.A. and Williams, L.A.J. (1972). Geology Of The Eastern Rift System of Africa. The Geol. Soc. Amer. Special Paper 136, 67 pp.

Belousov, U.V. (1971). On The Possible Forms Of Relationships Between Magmatism And Tectogenesis. Jour. Geol. Soc., 127, 57-68.

Bignell, R.D. (1975). Timing, Distribution And Origin Of Submarine Mineralization In The Red Sea. Trans. Inst. Min. Metall, 84, B1-B6.

Binns, R.A. Gunthorpe, R.J. and Groves, D.I. (1975). Metamorphic Patterns And Development Of Greenstone Belts In The Eastern Yilgarn Block, Western Australia. in Windley, B.F. (ed.). The Early History Of The Earth. Wiley and Sons.

Bird, J.M. and Dewey, J.F. (1970). Lithosphere Plate-Continental Margin Tectonics And Evolution Of The Appalachian Orogeny. Geol. Soc. Amer. Bull., 81, 1031-1060.

Bridwell, J. (1978). Physical Behaviour Of Upper Mantle Beneath The Northern Rio Grande Rift. in Hawley, J.W. (ed.). Guide-book To Rio Grande Rift In New Mexico And Colorado. New Mex. Bureau Of Mines And Mineral Resources, Circular 163.

Bridgewater, D., Sutton, J. and Watterson, J. (1974). Crustal Down Folding Associated With Igneous Activity. Tectonophysics, 21, 57-77.

Bridgewater, D. and Windley, B.F. (1973). Anorthosites, Post Orogenic Granites, Acid Volcanic Rocks And Crustal Development In The North Atlantic Shield During The Mid-Proterozoic. in Lister, L.A. (ed.)., Symp. On Granites,Gneisses And Related Rocks. Geol. Soc. S. Afr., Spec. Pub. 3, 302-318.

Brown, A.C. (1971). Zoning In The White Pine Copper Deposit, Michigan. Econ. Geol., 66, 543-573.

Brown, A.C. (1979). Stratiform Copper Deposits: Evidence For Their Post Sedimentary Origin. Min. Sci. Engng., 10, 3., 152-170.

Burke, K. and Dewey, J.F. (1973). Plume Generated Triple Junctions - Key Indicators In Applying Plate Tectonics To Old Rocks. Jour. Geol. 81, 406-433.

Burnham, C.W. (1979). Magmas And Hydrothermal Fluids. in Barnes, H.L. (ed.). Geochemistry Of Hydrothermal Ore Deposits. Wiley.

Carmicheal, I.S.E., Turner, F.J. and Verhoogen, J. (1974). Igneous Petrology. McGraw Hill.

Chase, C.G. and Glimer, T.H. (1973). Precambrian Plate Tectonics: The Mid-Continental Gravity High: Earth. Planet. Sci. Lett., 21, 70-78.

Constantinou, G. (1976). Genesis Of The Conglomerate Structure,Porosity And Collomorphic Texture Of The Massive Sulphide Ores Of Cyprus. in Strong, D.F. (ed.). Metallogeny And Plate Tectonics. Geol. Assoc. Canada., Spec. Paper 14, 187-210.

Crohn, P.W. (1975). Mineralization In The McArthur And Nicholson Basins, in Knight, (ed.). Econ. Geol. Of Aust. And Papua New Guinea, Aust. Inst. Min. Metal., Monograph 5, 327-329.

Gilbert, G.M. and Reynolds, M.W. (1973). Character And Chronology Of Basin Development, Western Margin Of The Basin And Range Province. Geol. Soc. Amer. Bull., 84, 2489-2510.

Goodwin, A.M. and Ridler, C.H. (1970). The Abitibi Orogenic Belt. in Baer, A.J. (ed.). Symposium On Basin And Geosynclines Of The Canadian Shield. Geol. Survey Of Canada. Paper 70-40, 1-31.

Green, G.H. and Ringwood, A.E. (1967). The Genesis Of Basaltic Magmas. Contr. Mineral. Petrol., 15, 103-90.

Groves, D.I. and McCarthy, T.S. (1978). Fractional Crystallization And Origin Of Tin Deposits In Granitoids. Mineral. Deposita, 13, 11-26.

Hafner, W. (1951). Stress Distribution And Faulting. Geol. Soc. Amer. Bull., 62, 373-398.

Hallam, A. (1972). Relation Of Palaeogene Ridge And Basin Structures And Volcanicity In The Hebridies And Irish Sea Regions Of The British Isles To The Opening Of The North Atlantic. Earth. Planet. Sci. Lett., 16, 171-177.

Harrison, J.E. (1972). Precambrian Belt Basin Of N.W. U.S. Its Geometry, Sedimentation And Copper Occurrances. Geol. Soc. Amer. Bull., 83, 1215-1240.

Heiken, G. (1976). Depressions Surrounding Volcanic Fields - A Reflection Of Underlying Batholiths. Geology, 4, 568-572.

Helgeson, H.C. (1968). Geologic And Thermodynamic Characteristics Of The Salton Sea Geothermal System. Amer. Jour. of Science, 266, 129-166.

Hoffman, P. Dewey, J.F. and Burke, K. (1974). Aulacogens And Their Genetic Relationship To Geosynclines, With A Proterozoic Example From Great Slave Lake Canada. in Dott, R.M. and Shaver, R.H. (ed.). Modern And Ancient Geosynclinal Sedimentation. Soc. Econ. Paleon. and Mineral. Spec. Pub. 19, 38-55.

Hurley, P.M. (1972). Can The Subduction Process Of Mountain Building Be Extended To Pan African And Similar Orogenic Belts? Earth. Planet. Sci. Lett., 15, 305-314.

Jackson, J.A. (1980). Reactivation Of Basement Faults And Crustal Shortening In Orogenic Belts. Nature., 283, 343-346.

Jacobsen, J.B.E. (1975). Copper Deposits In Time And Space. Mineral. Sci. Eng. 7, 337-371.

Jongsma, D. and Mutter, J.C. (1978). Non-axial Breaching Of A Rift Valley, Evidence From The Lord Hove Rise And The South Eastern Australian Margin. Earth. Planet. Sci. Lett., 39, 226-234.

Kanasewich, E.R. (1968). Precambrian Rift: Genesis Of Stratabound Ore Deposits. Science, 161, 1002-1005.

Kanasewich, E.R., Havskov, J. and Evans, M.E. (1978). Plate Tectonics In The Phanerozoic. Can. Jour. Earth. Sci., 15, 919-955.

Karig, D.E. and Moore, G.F. (1975). Tectonically Controlled Sedimentation In Marginal Basins. Earth. Planet. Sci. Lett., 26, 233-238.

Kay, M. (1951). North American Geosynclines. Geol. Soc. Amer. Mem. 48, 143 pp.

Kelley, V.C. (1977). Geology Of Albuquerque Basin, New Mexico. New Mexico Bureau Of Mines And Mineral Resources. Mem. 33., 59 pp.

Kent, P.E. (1977). The Mesozoic Development Of Aseismimic Continental Margins. Proc. Geol. Soc. Lond., 134, 1-18.

Morrissey, G.J. Davis, G.R. and Steed, R.M. (1971). Mineralization In The Lower Carboniferous Of Central Ireland. Trans. Inst. Min. Met., 80 B174-B185.

Muffler, L.J.P. and White, D.E. (1969). Active Metamorphism Of Upper Cainozoic Sediments In The Salton Sea Geothermal Field And The Salton Trough, S.E. California. Geol. Soc. Amer. Bull., 80, 157-182.

Murray, W.J. (1975). McArthur Lead-Zinc An Related Deposits. in Knight, R.L. (ed.). Econ. Geol. of Aust. and Paoua, New Guinea. Aust. Dist. Min. Metal. Monographs. I. Metals, 329-339.

Naldret, A.J. and Cabri, L.J. (1976). Ultramafic And Related Mafic Rocks, Their Classification And Genesis With Special Reference To The Concentration Of Nickel Sulphides And PGM. Econ. Geol. 71, 1131-1158.

Olade, M.A. (1975). Evolution Of The Nigerian Benue Trough: A Tectonic Model. Geol. Mag., 112, 575-583.

Page, D.C. and Watson, M.D. (1976). The Pb-Zn Deposit Of Rosh Pinah Mine, South West Africa. Econ. Geol., 71, 306-328.

Peredery, W.V. (1979). Relationship Of Ultramafic Amphibolites To Metavolcanic Rocks And Sepentinites In The Thompson Belt, Manitoba. Canada. Mineral., 17, 187-200.

Pitcher, W.S. (1978). The Anatomy Of A Batholith. Jour. Geol. Soc. Lond., 135, 157-182.

Pitcher, W.S. (1979). The Nature Ascent And Emplacement Of Granitic Magmas. Jour. Geol. Soc. Lond., 136, 627-662.

Pitman, W.C. and Talwani, M. (1972). Sea-Floor Spreading In The North Atlantic. Geol. Soc. Amer. Bull., 83, 619-646.

Plumb, K.A. and Derrick, G.M. (1975). Geology Of The Proterozoic Rocks Of The Kimberley to Mount Isa Region. in Knight, R.L. (ed.). Economic Geology Of Australia And Papua, New Guinea. Aust. Inst. Min. Metal. Monograph. I. Metals, 217-252.

Ramberg, H. (1971). Dynamic Models Similating Rift Valleys And Continental Drift. Lithos, 4, 359-276.

Ramberg, I.B. and Neuwman, E.R. (1978). (eds.). Tectonics And Geophysics of Continental Rifts. Proceedings Of The NATO Advanced Study Institute. Series C. Oslo, 1977.

Raybould, J.G. (1978). Tectonic Controls On Proterozoic Stratiform Copper Mineralization. Trans. Inst. Min. and Metall., 87, B79-B86.

Ross, J.R. and Hopkins, G.M.F. (1975). Kambalda Nickel Sulphide Deposits. in Knight, C.L. (ed.). Economic Geology of Australia and Papua, New Guinea. I. Metals. Austr. Inst. Mining Metal. Monograph. I. Metals, 100-121.

Runcorn, S.K. (1972). Dynamical Processes Of The Deeper Mantle. Tectonophysics, 13, 623-637.

Russell, M.J. (1976). Base Metal Mineralization In Ireland And Scotland And The Formation Of The Rockall Trough. in Tarling And Runcorn (eds.). Implic. of Cont. Drift. To The Earth. Sci. 1, 581-597.

Salop, L.E. and Scheinmann, Y.M. (1969). Tectonic History And Structures Of Platforms And Shields. Tectonophysics, 7, 565-597.

Sato, T. (1976). Origin Of The Green Tuff Metal Province Of Japan. in Strong, D.F. (ed.). Metallogeny And Plate Tectonics. Geol. Assoc. Canada. Spec. Paper 14, 105-120.

Scheibner, E. and Markham, N.L. (1976). Tectonic Setting Of Some Stratabound Massive Sulphide Deposits In New South Wales, Australia. in Wolf, K.M. (ed.). Handbook Of Stratabound And Stratiform Ore Deposits, 2, 55-77.

Scholz, C.M., Barazangi, M. and Sbar, M.L. (1971). Late Cainozoic Evolution Of The Great Basin, Western United States As An Ensialic Interarc Basin. Bull. Geol. Soc. Am., 82, 3979-3990.

Scrutton, R.A. (1973). The Age Relationship Of Igneous Activity And Continental Break-up. Geol. Mag., 110, 227-234.

Shackelton, R.M. (1976). Pan African Structures. Phil. Trans. R. Soc. Lond., 280, 491-497.

Sheridan, R.E. (1974). Conceptual Model For The Block Fault Orogeny Of The North American Atlantic Continental Margin Geosyncline. Geol., 2, 465-468.

Sims, P.K. (1976). Precambrian Tectonics And Mineral Deposits, Lake Superior Region . Econ. Geol., 71, 1092-1127.

Skinner, B.J., White, D.E., Rose, H.J. and Mays, R.E. (1967). Sulphides Associated With The Salton Sea Geothermal Brine. Econ. Geol., 62, 316-330.

Spencer, E.W. (1972). The Dynamics Of The Earth. Thomas Crowell Company. New York.

Steward, T.J. (1972). Initial Deposits In The Cordilleran Geosyncline, Evidence Of A Late Precambrian (850 my) Continental Sedimentation. Geol. Soc. Am. Bull. 83, 1345-1360.

Steward, J.H. (1976). Late Precambrian Evolution Of North America: Plate Tectonics Implications. Geology, 4, 11-15.

Sugisaki, R., Mizutani, S., Hattori, H., Adachi, M. and Tamaka, T. (1972). Late Palaeozoic Geosynclinal Basalt And Tectonism In Japanese Islands. Tectonophysics, 14, 35-36.

Sutton, J. (1977). Some Consequences Of Horizontal Displacements In The Precambrian. Tectonophysics, 40, 161-181.

Sutton, J. and Watson, J.V. (1974). Tectonic Evolution Of Continents In Early Proterozoic Times. Nature, 247, 433-435.

Talbot, C.J. (1971). Thermal Convections Below The Solidus In A Mantled Gneiss-Dome, Rhodesia. Jour. Geol. Soc., 127, 377-410.

Tatsumi, T., Sekine, Y and Kanehira, K. (1970). Mineral Deposits Of Volcanic Affinity In Japan: Metallogeny. In, Tatusmi, T. (ed.). Volcanism And Ore Genesis. University of Tokyo Press.

Thompson, R.I. and Panteleyev, A. (1976). Stratabound Mineral Deposits Of The Canadian Cordillera. in Wolf, K.H. (ed.). Handbook Of Stratabound And Stratiform Ore Deposits, 5, 37-100.

Turner, J.S. and Gustafason, L.B. (1978). The Flow Of Hot Saline Solutions From Vents In The Sea-Floor - Some Implications For Exhalative Massive Sulphide And Other Ore Deposits. Econ. Geol., 73 1082-1101.

White, W.S. and Wright, J.C. (1964). The White Pine Copper Deposit Onlonogan County, Michigan. Econ. Geol., 49, 675-717.

Whitcher, (1975). Dugald River Lead-Zinc Lode. in Knight, R.L. (ed.). Econ. Geol. of Aust. and Papua, New Guinea. Aust. Inst. Min. Metal. Monograph 5, 373-376.

Whittaker, A. (1975). A postulated Post-Hercynian Rift Valley System in Southern Britain. Geol. Mag., 112, 137-149.

Whitten, E.H.T. (1976). Rapid Shelf Sed. Cretaceous Phase Of Rapid Sediment Accumulation, Continental Shelf, Eastern U.S.A. Geology, 4, 237-240.

Williams, N. (1978). Studies Of The Base-Metal Sulphide Deposits at McArthur River. I. The Cooley And Ridge Deposits. Econ. Geol., 73, 1005-1035.

Wilson, and Rocha (1955). Geology And Mineral Deposits Of The Boleo Copper District, Baja California, Mexico. U.S.G.S. Prof. Paper., 273, 134 pp.

Wilson, I.H., Derrick, G.M. and Hill, R.M. (1972). Copper Mineralization In The Precambrian Cloncurry Complex Of North-West Queensland, Australia. Internat. Geol. Cong., Montreal 1972, Section 4, 234-240.

Withjack, M. (1979). An Analytical Model Of Continental Rift Fault Patterns. Tectonophysics, 59, 59-81.

Windley, B.F. (1977). The Evolving Continents. John Wiley and Sons.

Winkler, H. (1974). Petrogenesis Of Metamorphic Rocks. Springer-Verlag.

Van Bremmelen, (1976). Plate Tectonics And The Undation Model: A Comparison. Techtonophysics, 32, 145-182.

Veevers, J.J. (1977). Rifted Arch Basins And Post Break-Up Rim Basins On Passive Continental Margins. Tectonophysics, 41, 1-5.

Vogt, P.R. (1975). Changes In Geomagnetic Reversal Frequency At Times Of Tectonic Change: Evidence For Coupling Between Core And Upper Mantle Processes. Earth. Planet. Sci. Lett., 25, 313-321.

Zielinski, R.A. and Lipman, P.W. (1976). Trace Element Variations At Summer Coon Volcano - San Juan Mountains, Colarado And The Origins Of Continental Interior Andesites. Geol. Soc. Amer. Bull., 7, 1477-1485.