GEODYNAMICS OF THE CAPE FOLD BELT IN THE REPUBLIC OF SOUTH AFRICA, A SUMMARY

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Abstract. Two types of earlier deformed and metamorphosed basement participate in the Cape orogeny. The cover rocks were deformed by at least four dated pulses that produced co-axial structures by sequential folding from the Early Permian to the Middle Triassic. Regional metamorphic grade changes gradually from the unmetamorphosed unfolded foreland in the north over anchi-grades to greenschist facies along the present southern cost line of Africa. However, deformation styles and strain magnitudes change abruptly across the trend. To some extent this can be correlated with crustal weaknesses established by geophysical work. No evidence of associated igneous activity was found.

Introduction

The purpose of this project was to elucidate the dynamic history with particular reference to the relative involvement of basement and cover in the deformation. Evidence was sought to test whether this mobile zone answers to a gravitational, plate tectonic or other tectonic model.

Regional Setting

The Cape Fold Belt consists of two branches. The western comprises several open upright mega-folds, monoclines and normal strike faults, all trending north-northwest for some 300 km along the Cedarberg mountains which parallel the western Cape coast. The more intensely deformed southern branch, extending some 900 km east along the south coast, meets the western branch in the south-western corner of the African continent, just north-east of Cape Town. Topographically it comprises several east-west trending features: the coastal ranges in the south, followed progressively northwards by an intermontane basin, the inland ranges, a gradually southward slanting piedmont surface and finally the Great Escarpment (see Figure 1).

The stratigraphic sequence involved in this orogen can be subdivided into basement and cover according to the simplified scheme in Table 1.

Previous Knowledge

Folding

Folding has affected both Cape and Karoo Supergroup strata that are essentially conformable in this domain. The youngest units to be deformed are lower Beaufort beds probably deposited in mid-upper Permian times. The tectogenesis was therefore estimated to have taken place in the Triassic.

Between two major east-west trending anticlinoria that follow the mountain ranges, several double-plunging anticlines occur in the wide synclinorium of the intermontane basin. Mega-folds of several kilometres wavelength and amplitude extend for several tens of kilometres along strike with almost horizontal axes. An en-echelon arrangement may be observed. One limb can be overturned, dipping at 70°-80° south. The complexity and intensity of structure seems to increase eastwards, whereas the greatest width of the belt on land measures 170 km along 23°E longitude. Fold amplitudes in the lower Beaufort Group gradually wane northward of the interior range to disappear entirely at the foot of the Great Escarpment, where dolerite sheet and dyke intrusions of Jurassic age are prominently developed (see Figure 1).

The Table Mountain Group consists of two thick, pure quartz arenites separated by a thin, persistent shaly marker. The upper arenite exhibits disharmonic folding relative to the lower with decollement along the shale marker. Gravity could have played a role in shaping the second-order folds on overturned limbs of megastructures.

The mechanism of folding of quartzites was suspected to be one of simple shear along axial planes with dip-gliding and syntectonic recrystallisation of quartz (De Swardt et al., 1974). Gravity folding triggered by step-wise faulting had also been suggested (Newton, 1973).

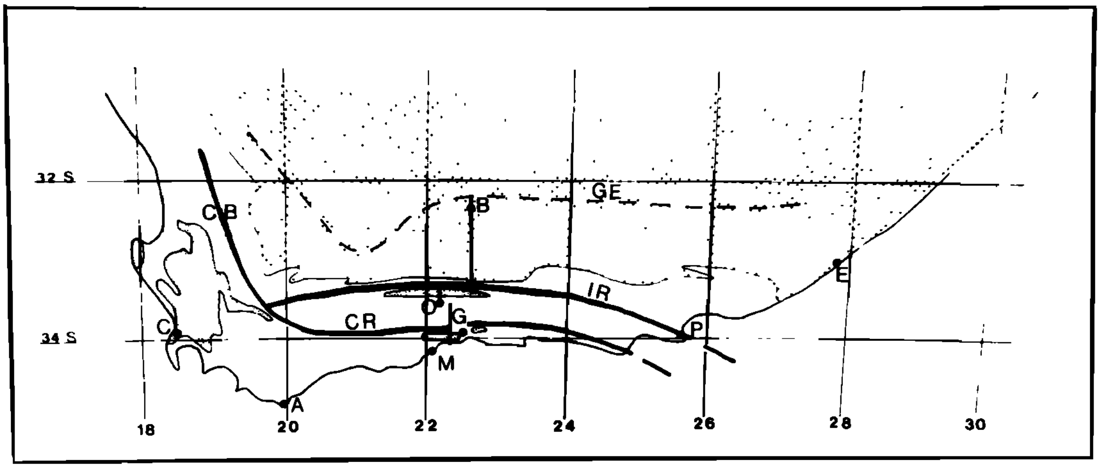

Fig. 1. Sketch map showing the main topographic and geological features around the southern tip of the African continent. The positions of the subsections of the composite profile between longitudes 22°E and 23°E (Figure 2) are shown. Small dots = Pre-Cape rocks; White = Cape Supergroup mainly; Large dots = Karoo succession; CB = Cedarberg range; CR = Coastal range; IR = Inland range; GE = Great Escarpment; C = Cape Town; A = Cape Agulhas; M = Mosselbay; G = George; O = Oudtshoorn; B = Beaufort West; P = Port Elizabeth; E = East London.

Other Observations

The single cleavage is axial planar and recrystallisation of micas has occurred along it (De Swardt et al., 1974; D.M. le Roux, 1974). Low angle thrusts dipping south have developed in the eastern parts of the Fold Belt around longitude 23°E (Theron, 1979). Their full extent and relationship to folding has not been established. High angle thrusting is very localised. Burial temperatures (De Swardt and Rowsell, 1974) have been estimated from illite crystallinity work on shales from deep boreholes drilled north of the inland range (Figure 1) in the zone of slight flexuring (zone ii in the cover rocks, see below and Figure 2). Here chlorite grade regional load metamorphism produced mimetic cleavage prior to deformation. Major faults of Juro-Cretaceous age with downthrow to the south cut the normal, gently south dipping limbs of many mega-anticlines or anti-clinoria, thus occasionally exposing erosion inliers of the basement over varying widths on the northern or up-throw side (De Villiers, 1941; Du Toit, 1954; Haughton, 1969; Truswell, 1977). The basement inliers had been regionally mapped and the composition of some of the intrusive granitoid rocks determined (Potgieter, 1950; Mulder, 1954). Little was known about the origin of the metasediments, even less about their metamorphism and structure. No radiometric ages of intrusion and metamorphism were available. Systematic sampling and structural-tectonic studies across the cover rocks in the Fold Belt had not been undertaken. Little was known about the rheologic state of basement and cover during orogenesis.

Models for the Tectogenesis

Two models had been proposed:- Step-wise east-west faulting uplifted blocks to the south. This resulted in northward gravity-sliding of basement over cover along the contact. The resulting decoupling effect left the basement largely passive (Newton, 1973 and 1974).

Single phase, tangential north-south shortening with heavy involvement of the basement (De Swardt et al., 1974; De Swardt and Rowsell, 1974).

Approach

To achieve maximum efficiency with the available means it was decided to concentrate on a geotraverse across the southern Cape Fold Belt between longitudes 22°E and 23°E (Figure 1) and extending for some 170 km from the coast up to the escarpment. Figure 2 represents a simplified and composite section along this traverse. Here two erosional inliers of basement are exposed north of major Cretaceous faults.

For a proper assessment of the complex structure and the relationship between intrusion, metamorphism and deformation, the basement rocks were remapped regionally and also locally in detail. Structural fabric analysis, petrographic and petrochemical work was co-ordinated with isotopic dating. The low grade metamorphic rocks of the northern inlier were also subjected to a stratigraphic and sedimentary analysis.

The cover rocks were mapped on a semi-regional to detailed scale along representative profiles. Style and fabric of structures were analysed.

TABLE 1. Simplified Stratigraphic Sequence from the Geotraverse

		LITHOSTRATIGRAPHY		THICKNESS KM	CHRONOSTRATIGRAPHY	AGE MA
	SUPER-GROUP	GROUP	LITHOLOGY			
COVER	KAROO	LOWER BEAUFORT	MUDSTONE AND SANDSTONE	7	PERMIAN	DEFORMATION
		ECCA	GREYWACKE & SHALE		LOWER PERMIAN	S_4 = 230 ± 3 S_3 = 247 ± 3
		DWYKA FORMATION	TILLITE		CARBONIFEROUS	S_2 = 258 ± 2 S_1 = 278 ± 2
			RIM OF BASIN ERODED			
	CAPE	WITTEBERG	SANDSTONE & SILTSTONES	7,5 - 13	CARBONIFEROUS	
		BOKKEVELD	SHALES & SILTSTONES		DEVONIAN	
		TABLE MOUNTAIN	ORTHOSANDSTONE		SIL. ORDOV.	440 FROM FOSSIL EVIDENCE
			MAJOR UNCONFORMITY, HIATUS 500		700 MA	
BASEMENT		NAMA; MALMES-BURY & INTR. GRANITOIDS	METASEDIMENTS	5 - 10	NAMIBIAN ERA	EARLIEST KANGO METAMORPHISM:- 755 ± 19
		KANGO;	GRANITOID	9		GRANITE INTRUSION INTO KAAIMANS:- 500 - 550 400 - 430
		KAAIMANS & INTR. GRANI-TOIDS				

Fold geometry received special attention and was combined with a micro-structural analysis of quartzites to trace deformation mechanisms, and derive stress-orientations. Cleavage morphology is correlated with illite crystallinity of pelitic rocks (Hälbich and Cornell, in press). This is supplemented by fluid inclusion measurements on pre- to syntectonic quartz veins to indicate temperature variations. Ar^{40}/Ar^{39} age spectrum analyses (Fitch et al., 1969) on shaly rocks reveal a lengthy and cyclic history of deformation. All this information is combined with the above-mentioned basement studies and latest geophysical parameters for the crust beneath the Fold Belt (De Beer and Gough, 1979) and seismic work in the cover rocks (Fatti and Du Toit, 1970) to outline the tectonic history of the cover rocks in the Cape Fold Belt. Repeated infolding provides good exposures with up to 1500-metres vertical relief.

Results

The Basement

The stratigraphies of the two basement inliers cannot be correlated (Figure 2). The Kango Group in the northern inlier represents a shallow water marine facies of immature greywackes, intraformational conglomerate and limestones (Mulder, 1954; Le Roux, 1977; Le Roux and Gresse, in press). The southern Kaaimans Group however, originally were fine-grained, well-bedded mature sediments, probably of deeper water origin (Gresse, 1976 and in press).

The Southern Inlier. In this area, some (90x 10) km^2 in size (Krynauw and Gresse, in press), various syn- to post-tectonic granitoid sheets apparently intruded the Kaaimans Group 500-550 Ma and 400-430 Ma ago (Rb/Sr and U/Pb minimum ages)

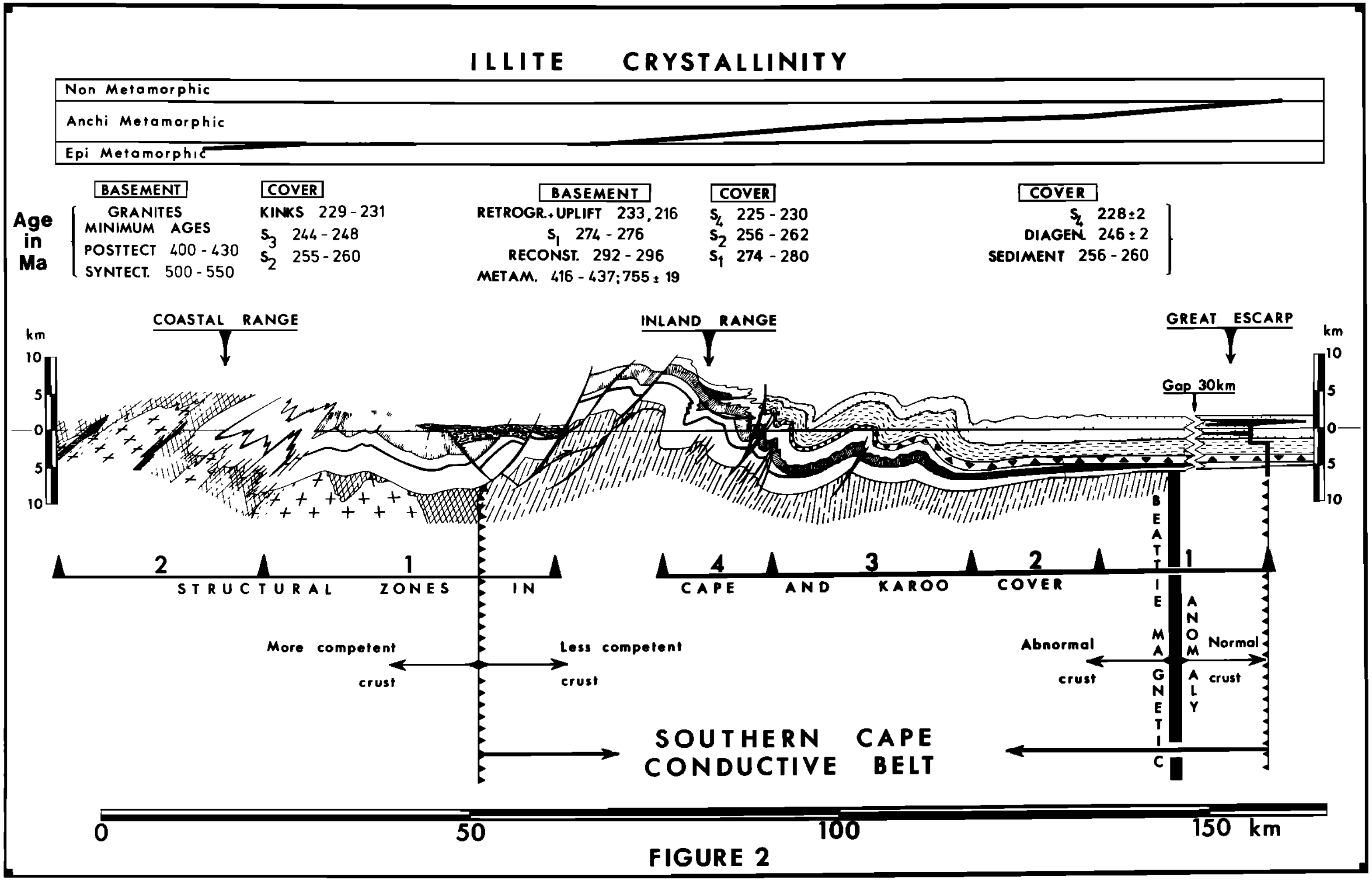

Fig. 2. Simplified, composite tectonic section from south (left) to north (right) across the southern Cape Fold Belt, showing basement, cover and crustal features. Dated tectonic and other events are shown as well as a metamorphic profile based on illite crystallinity. Vertical scale = horizontal scale. Topography omitted. Position of subsections making up profile are indicated in Figure 1.

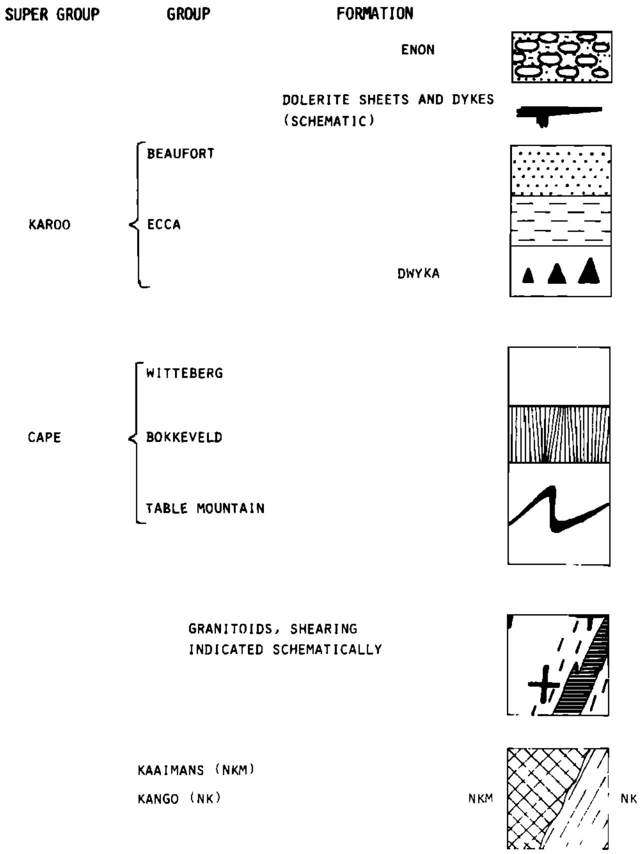

Fig. 3. Legend for Figure 2.

(Gresse, op cit; Krynauw, 1977 and in press; Krynauw and Gresse, 1980). These are minimum ages. Regional metamorphism reaching lower amphibolite grade is largely overlapped by contact metamorphic effects.

Three phases of horizontal, north-south directed compressive deformation are identified. These led to a dominant east-west trending and south-dipping foliation that affects all rocks except the cores of the thickest granite sheets and the latest intrusives. The first two phases have no equivalents in the cover rocks and produced a prominent S/L-tectonite with an a-fabric lineation due to crystallisation on the foliation during intrusion of the granitoids.

The third phase with east-west trending fold axes deforms the earlier foliations and lineations and is associated with late mylonitisation, cataclasis and brittle thrusting in the granitoids and competent metamorphites, but with extensive kinking in the fine-grained rocks. These features are similar to the structures found in the cover formations. Where comparable rocks of the two sequences are in contact, trend and style are identical. (Gresse, in press; Krynauw, in press; Krynauw and Gresse, 1980).

A final phase of north-south tension producing kinks, conjugate shearing and normal faulting is clearly associated with the regional Cretaceous dip-slip strike faults.

The Northern Inlier. The metasediments in this area apparently never exceeded greenschist facies metamorphism, and although the inlier measuring 140x15 km² (Le Roux and Gresse (a) and (b) in press) is larger than the southern one, the only intrusions found are basic sheets and dykes.

Again two phases of deformation pre-dating the Cape orogeny can be identified in places, though one of them, being an east-west trending B-tectonite with steeply south-dipping axial plane and cleavage, is dominant. The structures are isoclinal flow folds with near-horizontal axes and a well-developed a-fabric lineation in conglomerates (Le Roux, 1977 and in press). Evidence for overprinting by the Cape orogeny can be recognized only near the unconformity because pre- and post-Cape metamorphic grades and trends are very similar (Gresse, 1980; Le Roux and Gresse (b), in press).

Pre-Cape basic intrusives first became amphibolites some 755 ±19 Ma ago (Ar^{40}/Ar^{39} age spectrum) and then retrogressed to the greenschist facies 418 ±29 Ma and again around 211 ±17 Ma ago (Hälbich et al, in press).

Circumstantial and outcrop evidence reveals at least two major low angle thrusts in the Kango Group, one of which has probably been folded during the Cape orogeny. The sequence is also sliced by numerous east-west trending normal strike faults of Cretaceous age.

The Cover

North of the Inland Mountain Range. The fold intensity and style changes southwards in several clearly discernible stages (Figure 2). They are the following, proceeding from north to south.

Zone 1 is a zone of listric thrusting. Folds (wavelength, 1-2 km) have limbs inclined at less than 5°. Cleavage is absent except locally near leading edges of small thrust wedges (Coetzee, in press; Hälbich (b), in press). Internal micro-structure of quartz bears the imprint of both vertical loading and horizontal tectonism. The micro-fabric is synsymmetric with the meso-fabric, σ_1 being horizontal, N-S, σ_2 and σ_3 being interchangeable. Unsteady, cold-working conditions are indicated (Hälbich (b), in press). Horizontal N-S shortening by initial buckling and thrusting amounts to a few percent. Illite crystallinity work reveals that the rocks are unmetamorphosed or have reached the lowest and intermediate grades of anchi-metamorphism (Hälbich and Cornell, in press). Homogenization temperatures for nearly pure water (T_{Fr} = 0°C to 2°C) from two samples of pre- and syntectonic quartz-filled fissures of zones 1 and 2 occur between 140°C and 155°C. The quartz in these veins has a strong preferred crystal orientation that is directly related to their origin (Hälbich (b), in press). Some 5-6 km of Beaufort and overlying Stormberg Group rocks are estimated by extrapolation to have been eroded since the tectogenesis.

If a normal geothermal gradient was the only source of heat at that time and place, then the homogenization temperature T_H was very near the trapping temperature T_T, although, according to the derived load stress T_T should be about 90° higher (Roedder and Kopp, 1975; Kennedy, 1950).

The northern boundary of this zone against undeformed Karoo rocks intruded by dolerite dykes and sheets coincides with the northern edge of the Southern Cape Conductive Belt in the crust.

This edge is probably the transition in the basement from 1000 Ma Namaqua-Natal gneisses to the pre-Cape formations of Namibian age. The southern boundary of the zone of listric thrusting in the cover coincides with the Beattie magnetic anomaly in the crust. South of this anomaly the crust is abnormal as far as gravity and magnetic properties are concerned (Gough et al., 1973, and De Beer, in press).

Zone 2 is a zone of open symmetric and upright flexural slip folding (wavelength 1-2 km), with limb dips not exceeding 25°. A spaced axial plane cleavage S_4 (230 ±3 Ma) (Hälbich et al, in press) is developed in fine pelites only. Listric thrusts are present. Internal micro-structure of quartz is still simple, and synsymmetric with bedding and meso-fabric on both limbs of folds. Maximum principle stress σ_1 is N-S, parallel to bedding. Unsteady, cold working conditions are indicated (Hälbich (b), in press). Horizontal shortening by buckling alone is 7,5%. Minimum temperatures due to loading reached 140°C to 155°C as determined from fluid inclusions (see above). This zone and those following to the south (Figure 2) are all underlain by more than normally magnetic and highly conductive crust (Gough et al., 1973 and De Beer, in press), with abnormally low density.

Zone 3, a zone of intense, asymmetric and inclined class 1b flexural slip mega-folding (wavelenght 5-7 km), also displays internal longitudinal strains. One of the limbs has a near 90° dip and may be overfolded to the north. Homogeneous flattening of this limb has occurred in Beaufort and Ecca strata, with final elastic rupture and extension along the dip. A well-developed, faning axial plane cleavage S_1 (278 ±2 Ma) becoming slaty in the finest grained rocks, displays abundant evidence of dewatering (Gray, 1977, 1978), with final recrystallisation of new white micas parallel to it. A steeply south-dipping S_2 (258 ±2 Ma) solution or crenulation cleavage is also present. No recrystallisation effects are associated with the younger structure. Kink-bands (S_4 = 230 ±3 Ma) are the latest features indicative of N-S horizontal compression (Hälbich et al, in press). Quartz microstructures are complex. Several sets of Böhm lamellae and deformation lamellae occur and they may completely cloud the grains. This micro-fabric is asymmetric to bedding. Unsteady, mainly cold working and pulsating conditions with excessive strain hardening are indicated (Hälbich (b), in press). Horizontal shortening is around 30%, and upper anchi-metamorphic grades are reached (Hälbich and Cornell, in press). Temperatures are estimated to have been <300°C. This zone and zone (iv) are both underlain by magnetically abnormal and highly conductive crust.

Zone 4 is a zone of folding just as zone 3 above but with the following additional characteristics:

Extensive fore-limb and back-limb thrusts have developed. Second order cascade folding is prominent on overturned mega-limbs and bedding decollement is found on all scales (Coetzee, in press; Hälbich (c) and (d), in press). Quartz micro-structure is very similar to that in zone 3 except that microscopically thin bands are present in which steady, dynamic recrystallisation has occurred with annealing and consequent clearingup of grains (Hälbich (b), in press). Metamorphic grade touches the boundary of anchi- to epi-zone (Hälbich and Cornell, in press). Homogenization temperatures determined from fluid inclusions on syntectonic quartz veins of the Bokkeveld Group containing nearly pure water, form a distribution peak at 300°C. The occasional appearance of new biotite growing in S_1 corroborates the temperature estimate.

Some general remarks and deductions apply to the structural zones outlined above. Shallow seismic refraction (Fatti and Du Toit, 1974) confirms the subdivision of the first two zones throughout the cover rocks. The sudden inception of intense mega-folds in the third and fourth zone is probably due to the rapidly southward thickening Table Mountain Group which takes the role of dominant member in this cover sequence. In this same area, first the Beaufort Group, then also the Ecca Group thin rapidly southwards, and this may contribute to the abruptness of the northern boundary of zone 3. The "explosive" stage of folding was evidently reached from here southwards during a first event around 278 ±2 Ma and sequential folding triggered by inherent weaknesses in basement and cover alike may have controlled the variations in fold intensity. This was substantiated by dating four cleavage events.

Additional thrusting in zone four is accounted for by dewatering of these rocks at higher burial temperatures as compared to zone three. Evidence for extensive dewatering of the sediments is seen everywhere along the oldest cleavage in any particular sector right from the first inception of this structure through all the intermediate stages. Only in the final stage reached in zones three and four, is this mechanism superseded by recrystallisation of illites within the cleavage itself (Hälbich and Cornell, in press).

From the Coastal to the Inland Range. The intermontane valley is underlain by a synclinorium with open folds in the Bokkeveld Group, here covered by conglomeratic Cretaceous infill of a yoked basin. Although the intensity of folding is low, strain marker fossils indicate up to 30% of internal, horizontal shortening. This is corroborated by the intense, omnipresent axial planar S_2 cleavage. The metamorphic grade touches on epi-zonal. Temperatures are estimated at around 300°C from illite crystallinity (Hälbich and Cornell, in press).

The southern edge of the Southern Cape Conductive Belt (De Beer, in press) forms the northern boundary of this area and is more or less coincident with the Kango fault zone. The crust underlying the synclinorium south of the Conductive Belt is on geophysical grounds (Gough et al., 1973; De Beer and Gough, 1979) more competent than that within the latter, and this may go a long way to explain the difference in fold styles of the cover rocks. The change in competency of the crust may be explained by assuming that the area to the north consists of Kango-type crust more than 755 Ma old and never intruded by granites (Hälbich et al, in press). The southern crust however, comprises Kaaimans-type formations intruded by late Precambrian to Cambrian granitoids and metamorphosed to much higher grades, thus becoming stiffer and more competent (Krynauw and Gresse, 1980; Gresse, in press; Krynauw, in press).

The coastal range in the study strip is a zone of acute to isoclinal class 2 folds (Ramsay, 1967) with axial planes inclined at low to intermediate angles southwards. Almost all rocks have developed an intense axial planar S_2 (258 ±2Ma) cleavage (slaty in pelites) which is intersected by a co-axial shear or crenulation cleavage S_3 (247 ±3 Ma) dipping steeply south. Finally kinks (230 ±3 Ma) have been produced by horizontal, N-S compression (Hälbich et al, in press; Hälbich (c), in press). A prominent mineral lineation is seen along dip direction on the cleavage. Quartz grains are completely annealed with a polygonal texture. The almost strain-free, clear grains of equal dimensions have an elongation parallel to the lineation. A relict internal quartz fabric (revealed by inclusion trains transecting new grain boundaries) is complex and oblique to the meso-fabric (Swart, in press). This is reminiscent of the asymmetric quartz micro-fabric in zones 3 and 4 above. Horizontal shortening, taking homogeneous flow into account, is around 70%. Epimetamorphic grades (greenschist facies) were reached with biotite forming in the S_2 plane. No recrystallisation of micas occurred during later paroxyms. Maximum temperatures are estimated at around 350°C from microstructure and illite crystallinity (Hälbich and Cornell, in press).

The crust is thought to be similar to that underlying the synclinorium to the north. It is clear that the Kaaimanstype basement participated in the Cape orogeny. A northward directed shear component produced flowage along axial planes and recrystallisation in the cover rocks under near equilibrium conditions during the formation of S_2. The basement reacted partly by refolding but to a considerable extent by elastic rupture (De Swardt et al., 1974: Gresse,]976 and in press; Krynauw and Gresse, 1980). This difference in mechanism is explained by the fact that the basement underwent at least its third deformation, and that these rocks were much drier than the cover sequence, on account of their higher pre-Cape metamorphism.

The reasons for the extra shearing in the coastal zone remain obscure, but several possibilities exist:

The style and intensity of deformation can be expected to change with increasing temperature in the belt. At certain temperatures, stresses and internal fluid pressures, critical strain rates are reached. It is possible that at temperatures around 350°C for quartz the triggering influence for the coastal anticlinorium came from some pre-existing but undetected weakness in the crust. So far there is no geophysical evidence for this.

Conclusion

Although this is considered a representative traverse, it is only one of many that are needed to provide conclusive answers to all the objectives stated at the beginning.

The following are considered to have been established:

There are abrupt changes in style and intensity of deformation of cover rocks across the Cape Fold Belt.

Deformation intensity is 25%-30% (Halbich, 1977, 1978) but may reach 70% locally where recrystallisation has occurred.

In several cases these variations can be correlated with geophysical and geological evidence for changes in the type of basement.

There is direct and indirect evidence for participation of basement in, if not control over, the intensity and positioning of deformation in the cover rocks.

Fabric and kinematic analysis reveals that the tectonite has very regular trends. Four consecutive pulses are recognised. They produced horizontal northward compression directed against a 1000 Ma old basement. The thickness of crust involved in deformation was some 20 km.

From the northernmost appearance of "explosive" folds southwards, the metamorphic grade increases to indicate that beyond the present-day coastline even higher grades than lower epi-zonal can be expected.

The deformation reached its first paroxysm some 278 ±2 Ma ago when the earliest S_1 cleavage originated. A main phase of relative S_1 = absolute S_2 formation occurred in other places around 258 ±2 Ma ago. A 247 ±3 Ma episode is responsible for S_3 (absolute), and a final pulse (230 ±3 Ma) produced either kink-bands or a solution cleavage in all parts of the orogen. The tectogenesis therefore extended over at least some

45-55 million years. Taking the average strain as 30%, average strain rate e = 2 x 10^{-16}/sec. (Hälbich (e), in press). In highly deformed sectors of the fold belt such as the coastal range, the first two paroxysms are separated by only 13 Ma. Therefore strain rate here is one order of magnitude higher.

The distribution of S_1 ages indicates that folding was sequential, triggered in the belt at sites of least resistance. The northernmost disturbance were only caused during the final stage.

Field evidence combined with fabric analysis and age of cleavage shows that the Dwyka tillite was still unconsolidated during the first paroxysms about 278 ±2 Ma ago. The lowermost Beaufort Group was probably compacted around 247 ±3 Ma ago and cleaved 230 ±3 Ma ago by dewatering along the very crude spaced cleavage.

Any geodynamic model for the Cape Fold Belt will have to take the above results into account. All evidence points to a relatively short event (compared to other orogenies) starting in the Early Permian and lasting into the Middle Triassic. It was a pulsating, deep-going deformation involving the basement. Temperatures exceeding epizonal can be derived only by extrapolation to regions beyond the present southern confines of the continent. No evidence for associated igneous activity beyond the known traces of ashfalls from the Karoo sequence was found (Lock and Johnson, 1974; Elliott and Watts, 1974; Martini, 1974).

It is concluded that the exposed part of the southern Belt gives evidence of a cycle of proper crustal shortening, that is not comparable with Jura foreland folding leaving the basement uninvolved. Therefore, the Belt should be seen as a Permo-Triassic orogeny with its own outstanding characteristics. Without further assumption (Lock, 1980) it is considered atypical of plate collision models, but more indicative of embryonic intraplate mobility (Hälbich (f), in press).

A fuller account of the Cape orogeny and a discussion on the merits of various tectonic models is being prepared as a special volume by the Geological Society of South Africa.

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