

# Stress patterns in the Cape Fold Belt

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## ABSTRACT

Rocks outcropping north of the Worcester Fault near Worcester, South Africa, belong to the Malmesbury Group and the Peninsula Formation of the Table Mountain Group. These exposures were studied to get an idea of their structural evolution.

Flattening strains produced the planar fabrics in the rocks, with flattening being the dominant deformation mechanism resulting from successive compressive events. This flattening was responsible for the preferred attitude of the rocks and the compressional crenulation cleavages. The compression direction varied from NE-SW to NW-SE during the formation of the composite foliations during the Saldanian Orogeny. These foliations were subsequently crenulated during the Cape Orogeny.

In general, NW-SE directed compressional stresses produced the deformation in the Peninsula Formation, where  $\sigma_1$  is oriented NW-SE. Extension direction is perpendicular to this, i.e. NE-SW. For the Malmesbury Group of rocks, NW- directed compressive stresses produced the fabrics in these rocks, with the extension direction being approximately perpendicular to this compressive direction. In general, it would appear as if the regional stress field varied somewhat in its orientation, and the structures in the Malmesbury rocks developed as a relatively continuous sequence of events within a geologically short period of time. It is also very clear that the later Cape Orogeny had a profound effect on the Malmesbury basement rocks, with stress orientations of the former influencing those of the latter.

**Key words:** Stress Patterns, Cape Fold Belt, Malmesbury Group, Table Mountain Group, Compressional Stresses

## INTRODUCTION

A synthesis of various studies of the Cape Fold Belt can be found in the compilation of Söhnge and Hälbich (1983) and De Wit and Ransome (1992).

The aims and objectives of this study are the following:

To do a macro-structural analysis of that part of the Malmesbury Group of which detailed structural analysis is lacking in the syntaxis, and to place this analysis in the tectonic context of the Cape Fold Belt and Saldanian Orogeny as a whole in order to contribute towards the knowledge of the structural evolution of the Boland Terrane. In this respect, major planar structures (foliations, bedding, folds, and joints) and linear structures (lineations, boudinage, faults, fold axes) were analysed and interpreted in detail.

An attempt was made to quantify the stress and strain in the region and see how the macro- and micro structures in the area accord with these axes. The orientation of the stress axes are an important indicator of the attitude of

present structures and indicate the degree of rotation of these axes during later fault activities.

Geological sequences in the study area north of the Worcester Fault range from Pan-African ages (800-500 Ma) through to the Cretaceous. These rocks belong to three major groups: the Pre-Cape basement inliers of the Malmesbury Group which is often associated with major faults, the Cape Supergroup mountains and a small sliver of the Uitenhage Group which outcrops on the fault plane.

In the Western Cape, the Precambrian Malmesbury Group has been divided into three tectonic terranes separated from each other by two northwest-trending fault zones. The Peninsula Formation represents the Table Mountain Group of the Cape Supergroup. It forms the mountainous ridges and landscapes of the Langeberg mountain range, which dominates the landscape north and southeast of Worcester. These rocks rest unconformably on the Brandwacht Formation of the Malmesbury Group. In the Worcester region, the

Enon Formation represents the Uitenhage Group of rocks, which is a conglomeritic unit.

## METHOD AND RESULTS

Field data were plotted on 1:50000 topographical maps and aerial photographs, and also on 1:10000 orthophotographs. Digitized data from the aerial photographs and structural data were plotted using ArcView GIS. For planar fabrics, directions of dip/dip were recorded, and the trend and plunge of linear fabrics were recorded using a standard Freiburger compass. By making use of standard structural computer programs (Rockware), lower hemisphere equal area projections were obtained for fabric data, rose diagrams from joint orientations and eigenvalue plots compiled from the stereonet statistics. Strain values and the orientation of principal strain axes were obtained by using the "orientation tensor method" which uses planar orientations to yield finite strain values. In other words, the two-axis ratio eigenvalue plots can also be used to relate fabric-shape change to progressive strain, and these values are obtained as standard from the statistical data yielded by the software programs to analyse the fabric data. Eigenvalue diagrams were obtained after the orientation measurements of planar features were plotted using the above-mentioned software packages. Strain values cited for the Peninsula Formation and the Malmesbury rocks were calculated from the eigenvalues obtained for the various orientation data. These strain values were calculated from tables produced by Harvey and Laxton (1980). The orientations of the stress axes were obtained by using the method advocated by Ramsay (1967) and Ramsay and Huber (1989, p.641-651).

Principal stress orientations were obtained after plotting the joint data as outlined previously. For the Peninsula Formation, the maximum compressive stress direction (axis),  $\sigma_1$ , is oriented WNW-ESE ( $096\backslash 28^0$ ), with the minimum compressive stress direction  $\sigma_3$  roughly perpendicular to it in the horizontal plane. At a few localities, the maximum compressive stress axis is oriented NNE-SSW.

When all the joint data of the Malmesbury rocks are plotted together, the maximum compressive stress axis  $\sigma_1$  is oriented almost N-S ( $177/17^0$ ), but it is obvious from the data that the stress axis orientation has varied considerably, from NE-SW to NW-SE. This is a clear indication that the later Cape Fold stress orientations have had a pronounced influence on the basement rocks.

In the Peninsula Formation, strain values derived from the eigenvalues indicate strain of the apparent flattening type on the Flinn diagram (oblate ellipsoids) with  $b$  exceeding  $a$  in value by several orders of magnitude, where  $a = (1+e_1)/(1+e_2)$ , and  $b = (1+e_2)/(1+e_3)$ ,  $e_1$ ,  $e_2$  and  $e_3$  being the principal strains (Ramsay, 1967).

In the fold hinges where the strain is of the apparent constrictional type,  $a$  exceeds  $b$  in value (prolate ellipsoids). The XY-plane, i.e. the principal plane of the strain ellipsoid, is parallel to the mean orientation of the bedding plane of the Peninsula Formation. In general, the strain values are very high.

Similarly, the strain pattern in the Malmesbury rocks derived from the eigenvalues reflects those in the cover rocks. The main foliation defines a strong preferred orientation, producing predominantly clusters of poles to planes on the stereo plots. Furthermore, the data define a strong cluster with  $b$  exceeding  $a$  in value by several orders of magnitude, implying a strong oblate ellipsoid on the Flinn diagram (field of apparent flattening). Where the data defines a prolate ellipsoid (field of apparent constriction),  $a$  exceeds  $b$  in magnitude and the data plots as a girdle. Once again, the XY-plane of the strain ellipsoid is parallel to the main foliation plane in the Malmesbury Group of rocks. The main foliation defines a strong preferred orientation, producing predominantly clusters of poles to planes as a result of the successive compressive deformation phases.

## CONCLUSIONS

It can be concluded that the Malmesbury Group of rocks have been formed in conditions similar to the descriptions of an elongate fan and a slope-apron system, following the model presented by Stow et al., 1985. An elongate fan is formed in a medium to high input of mixed-sized grades, but with mud and very fine sand dominant. The slope-apron system has a low-to-medium sediment supply rate, a mixed sediment type that is sand and gravel-rich in very small tectonically active basins, but may be mud dominated along muddy continental slopes (op cit). Rocks of the Peninsula Formation contain both an assortment of fine-grained as well as coarse-grained sediments, and also texturally and chemically immature sediments. This, together with the lateral and aerial extent of the Formation and Group, renders it an ideal candidate for a marine, and particularly a shallow marine origin.

Four distinctive foliation (cleavage) planes have been described in the Malmesbury Group of rocks, and are associated with the compressive Saldanian orogeny, with the two minor cleavages regarded as fracture cleavages associated with the later Cape Orogeny. The closeness in orientation of the latter to the former is explained by the similarity in maximum stress orientations between these two orogenies. The formation of the foliations, which can be considered as "composite foliations", is concluded to have been formed from a fairly constant stress field in magnitude, generally compressive which changes in orientation to form the variously oriented foliations. The deformational events of the Saldanian orogeny can be described as successive deformation phases in one

orogenic cycle, where the total deformation is built up of a series of separate pulsatory, compressive deformations. The foliations in the Malmesbury Group of rocks can be classed as composite foliations formed under progressive deformation, with structures having formed as a relatively continuous sequence of events. This implies that the total deformation is derived from a series of separate pulsatory, compressive deformations. The structures formed in the Malmesbury rocks have similar morphologies, and formed under similar metamorphic conditions.

Structures in the study area appear to have been formed as a result of compression during deformation, with the stresses falling dominantly within the thrust or reverse faulting stress regime with  $S_{Hmax} > S_{hmin} > S_v$ . For the condition of tectonic extension, the vertical normal stress is the maximum compressive stress  $\sigma_1$ , and for tectonic compression, the vertical normal stress is the minimum compressive stress  $\sigma_3$  (Twiss and Moores, 1999, p.190). For the Coulomb fracture criterion, for thrust faults,  $\sigma_3$  must be vertical, and for strike-slip faults,  $\sigma_2$  must be vertical (Twiss and Moores, 1999, p. 202). From the stress orientations obtained in this study, it is apparent that the  $\sigma_3$  stress orientation is the one that closest approaches the vertical.

The model to explain the formation of the structures in this region entails north-south compressive stresses associated with subduction within the context of Gondwana, resulting in the development of composite foliations  $S_1$ - $S_3$  (Saldanian Orogeny) related to three episodes of deformation. Within the overriding plate and away from the subduction zone, deformation was accomplished by means of shortening in the overriding plate. This was followed by the deformation associated with the formation of the Cape Fold Belt. The Cape Orogeny also influenced the Malmesbury basement rocks, and reactivated these earlier structures, forming the fracture cleavage  $S_4$  found in the Malmesbury rocks. These compressive events had a pre-stressing effect on the rocks, resulting in episodes of extension responsible for large-scale faulting in the region. The combination of compression (thrusting) and rifting (strike-slip faulting) is known as transpression, and is reported on various Gondwana Continents (Trouw and de Wit, 1998, Johnston, 2000, Curtis, 2001 and Paulsen et. al., 2004).

It is possible that the Namaqua-Natal basement to the north also influenced tectonic events further south, and the shape of this basement influenced the development of the syntaxis. The two fold trends in the Cape Fold Belt remain somewhat enigmatic, and a number of mechanisms for its formation have been advanced. The model proposed above also incorporates a mechanism for the formation of the Cape Fold Belt. In order to explain the two orientation trends of the Fold Belt, it is proposed that "coupling" takes place at the subduction zone, probably as a result of obduction or some other mechanism at this zone. This "coupling" causes a

sticking effect in the zone of shortening in the overriding plate, resulting in a dextral rotation of the western block and the formation of the western branch of the Cape Fold Belt and the syntaxis zone, accompanied by right-lateral shearing in the southern branch as the Falkland Islands moved southwestwards. In this way, there is a migration of the stress field which accounts for the differential stress field and structures across the Belt. This is analogous to an oblique collision with a rigid indenter as proposed by van Bever Donker (1991) for the Namaqua Province. The rigid indenter is in the form of the stable 3Ga Kaapvaal Craton situated at the centre of the subcontinent during Gondwana times. Compression in the continent interior, related to coupling of the plates during subduction at the Gondwana margin, resulted in the younger crustal material colliding with the stable interior of the Continent. This collision in the continent interior resulted in a differently orientated stress field, the two branches of the Fold Belt and the observed trend of the structures in the syntaxis region. Accretion of various landmasses onto the stable continental interior in southern Africa has been extensively reported in the literature.

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