Multiple deformation patterns in the Otjosondu manganese mining area, eastern Damara Belt, Namibia

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In the southern Central Zone of the western part of the inland branch of the Damara Orogen, early fold phases are difficult to identify because of intense D_2 and D_3 overprinting. In the east, however, at Otjosondu, the D_3 event is much less intense; early fold generations are therefore more easily identified. The D_1 phase of deformation in the study area is accompanied by an appreciable component of simple shear, and a poly harmonic suite of F_1 folds has developed. Recumbent to inclined as well as upright tight and upright open folds have been recognized. The variation in orientation and style of D_1 folds and the angle of 40-60° between the D_1 and the D_2 shortening directions result in contrasting styles of superposed fold patterns between these two generations. The superposition of D_2 folds on recumbent D_1 folds led to the development of dome-crescent mushroom interference patterns. In contrast, depending on the interlimb angle of upright D_1 fold morphologies, these D_1 folds either preserved their original D_1 trend or have been reactivated and reorientated to differing extents by fold hinge migration during D_2 deformation. The orthogonal superposition of D_3 warping on D_2 folds led to distorted dome-and-basin interference fold patterns. Brittle deformation fabrics have been observed as a conjugate set of sinistral and dextral arrays of shear fractures. A set of horizontal stress-release fractures developed predominantly in quartzitic lithologies. D_2 and D_3 folds are correlated with obvious fold patterns developed throughout the Central Zone. The D_1 phase has only been recognized close to the Okahandja Lineament. Elsewhere in the inland branch this reactivation of 01 folds by the D_2 deformation phase may explain why the identification of D_1 folds has been difficult.

Introduction

Where multiple superposition of deformation events occurs, the mechanism of superposed folding depends largely on the type of folds produced during the first deformation event and the angle between the successive compression directions (e.g. Ramsay & Huber, 1987). The study area exhibits interference patterns of three ductile deformation phases. The morphology of each fold generation and different angles between these three main shortening directions led to contrasting styles of superposed folding between the successive fold generations. In the eastern Damara Belt where outcrop is poor, mining activities have exposed a manganese ore-bearing horizon as a specific structural marker. Variables which influence the mechanism and degree of fold superposition can therefore be analysed in this region. The structural analysis summarized in this paper is described more fully elsewhere (Bühn *et al.*, *in press*).

The Otjosondu manganese deposits are situated at the eastern extent of the inland branch of the Damara Orogen (Fig. 1). The study area forms part of the southern Central Zone which is bounded to the south by the Okahandja Lineament. The ore-bearing horizon consists of haematite-rich iron formations with essentially two manganese ore horizons at the bottom and the top, respectively. This formation is 'sandwiched' between quartzitic units, termed the Upper and Lower Quartzites (Fig. 2). The entire sequence has been metamorphosed to upper amphibolite facies grade.

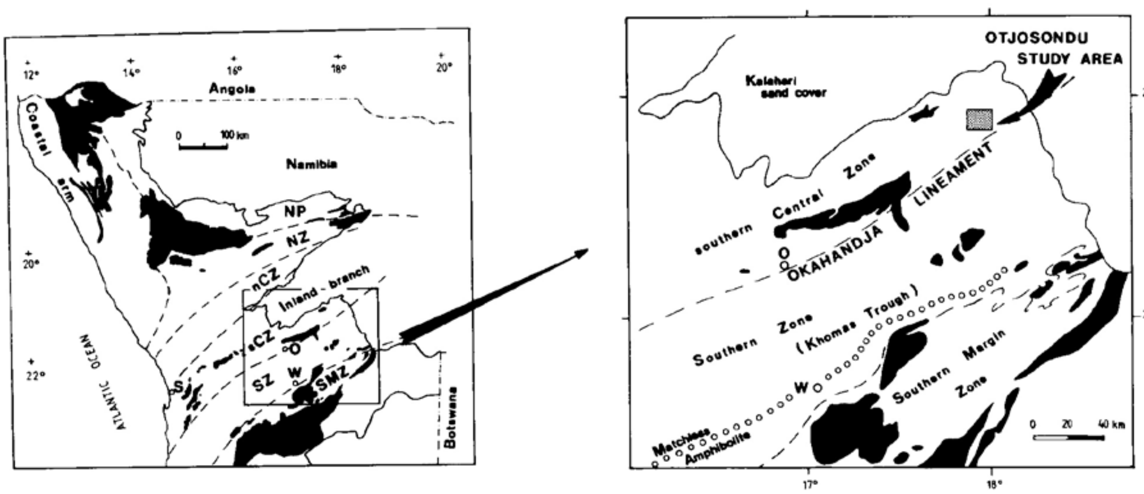


Fig. 1: Location map of the study area in the southern Central Zone of the inland branch of the Damara Orogen. O = Okahandja, W = Windhoek, S = Swakopmund; NP = Northern Platform, NZ = Northern Zone, n/s CZ = northern/southern Central Zone, SZ = Southern Zone, SMZ = Southern Margin Zone.

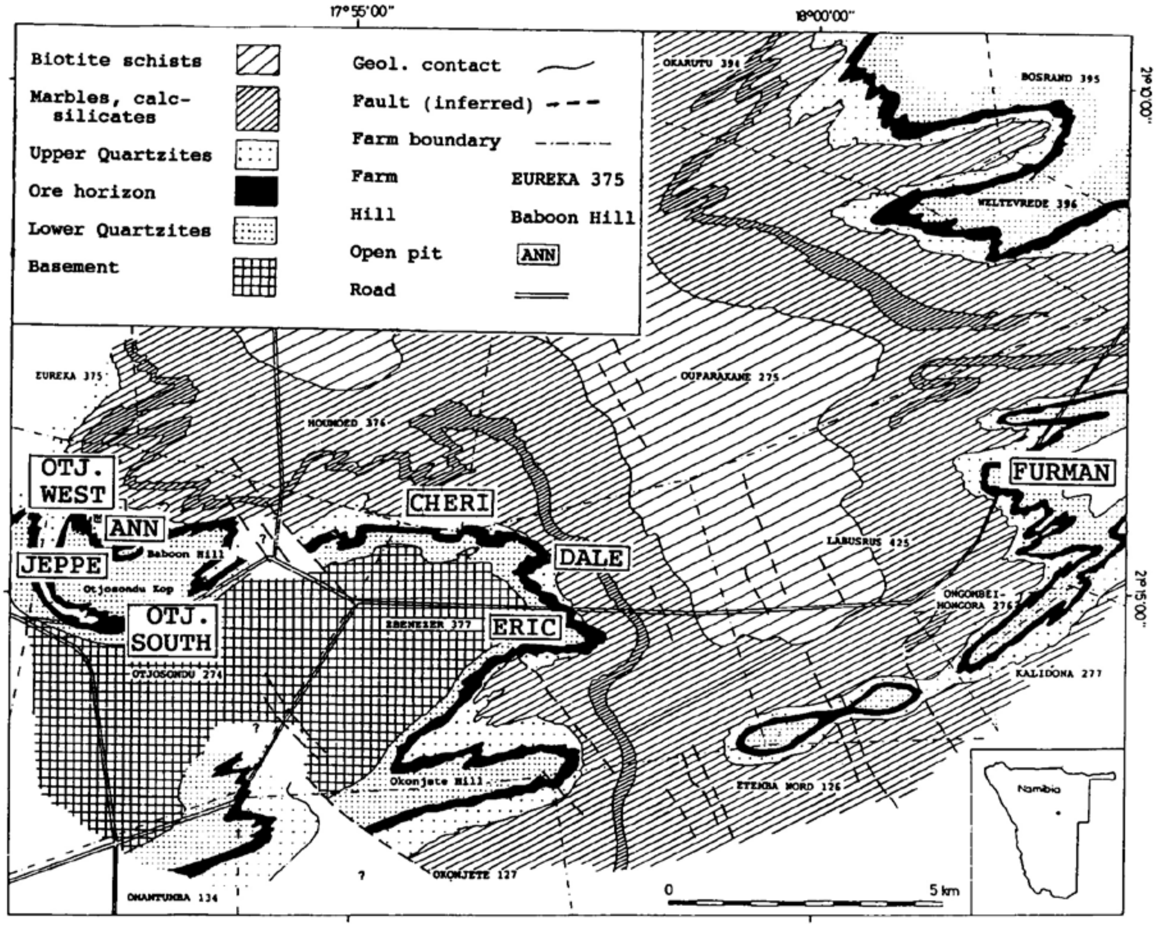


Fig. 2: Geological map of the Otjosondu manganese area, based on recent aerial photograph evaluation and information from Roper (1959). Note the area of classic crescentic fold superposition at Otjosondu Kop and the scatter of pre-D_3 hinge orientations especially in the area of Furman mine open pit.

Chronology of folding events

The outcrop patterns shown in Fig. 2 indicate a large NNW-trending synform of the latest deformation event D_3 which can be correlated with smaller scale open folds on the outcrop scale. Major pre-D_3 folds are developed on the scale of kilometres and plunge in opposite directions on either limb of the D_3 syncline. The NNW-oriented D_3 folds are superposed on the major regional ENE trend of previous folds and thus indicate an approximate 90° angle between the two shortening directions.

The pre-D_3 tectonic evolution in the study area consists of two fold generations. This is well illustrated in the area around Otjosondu Kop (Fig. 2), which shows superposed folding of the D_1 and the D_2 fold generations prior to D_3 warping. Certain features of pre-D_3 fold structures elsewhere in the Otjosondu area, however, show that classic superposed folding is not the predominant interference mechanism between F_1 and F_2 folds. The reasons for this will be outlined after the successive fold generations have been described.

D_1 deformation

The D_1 deformation has produced folds on all scales ranging from centimetres to kilometres in wavelength. Upright, open and tight, recumbent D_1 folds within the strata result from high competency contrasts between adjacent layers, and a considerable amount of simple shear deformation along subhorizontal planes has re-

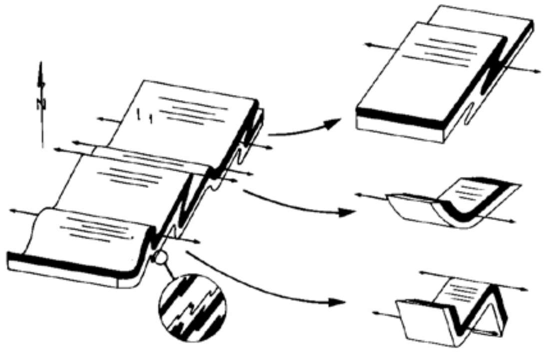


Fig. 3: D_1 polyharmonic folding in the study area. Overturned to recumbent NNE-verging folds as well as upright folds (open or tight) are illustrated.

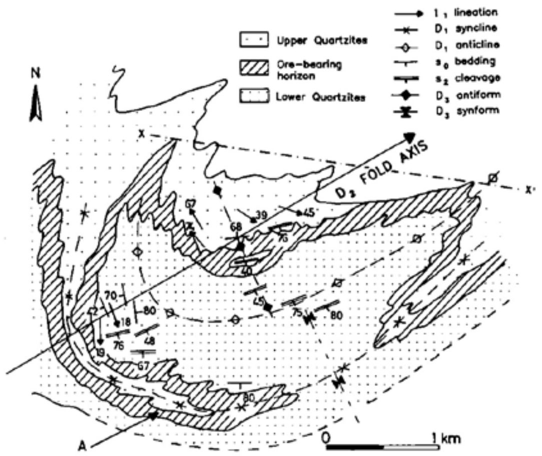


Fig. 4: Crescentic D1/D2 interference patterns at Otjosondu Kop. (A) indicates a D2 antiformal syncline. The join XX' is the inferred D1 fold hinge orientation.

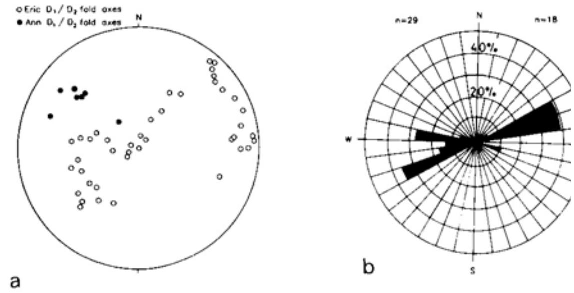


Fig. 5: Pre-D3 fold axis orientations. (a) Stereoplot of small medium-scale pre-D3 fold axes from the western portion the study area. Note the dispersion of fold axes with oppo plunges resulting from D3 folding; Schmidt net, lower he sphere. (b) Directions of plunge of large-scale pre-D3 f hinges from the entire Otjosondu mining area plotted on a r diagram. Two distinct modes trend ENE and WNW wit variation between them.

sulted in polyharmonic fold styles (Fig. 3). This diversity in D_1 fold morphologies is important for understanding the mechanism of D_2 superposition discussed later.

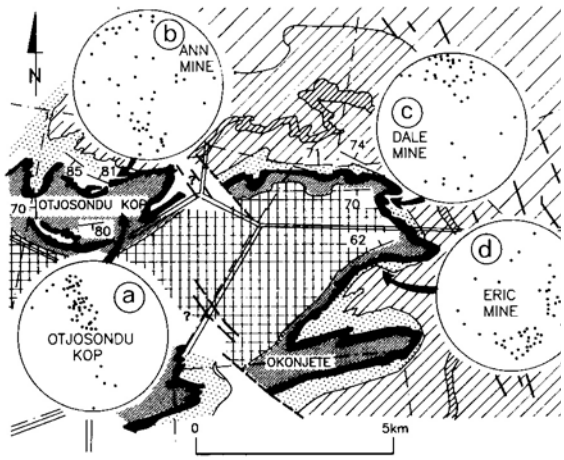
An oblate quartz crystal shape fabric defines a planar s_1 foliation and, locally, well-oriented apatite inclusions mimic this fabric within coarsely recrystallized quartz grains. This fabric is particulary well developed in pelitic and quartzitic lithologies. A prominent l_1 lineation, produced by the intersection of cleavage with bedding planes, parallels the D_1 fold axes. The orientation of the D_1 fold hinge line can be determined at Otjosondu Kop by joining the refolded closures of the earliest fold phase (join X-X' in Fig. 4), giving an ESE-trending fold hinge line. The D_1 folds face towards the NNE, indicating a vergence in this direction.

D_2 deformation

D_2 folds are predominantly of medium to large scale and trend ENE. Folds are tight to isoclinal, upright with axial planes mostly dipping steeply towards the SSE. The character of the D_2 deformation is best revealed at Otjosondu Kop (Fig. 4), where the refolding of recumbent D_1 folds into a superposed D_2 syncline creates upward- and downward-facing synforms with respect to the D_2 fold axis. This large-scale isoclinal D_2 fold plunges moderately to the ENE. On a smaller scale, isoclinal refolding of D_1 folds by the D_2 phase can be recognized where contrasting competencies of quartzitic layers and haematite quartzites are interlayered. The s_2 planar element in quartzites is defined by an oblate shape fabric of the quartz grains. This represents a subsequent coarse recrystallization, and the original s_2 cleavage planes have been modified and partly obliterated.

Superposition of D_2 on D_1

Pre-D_3 folds show a considerable variation in fold



trends from ENE to ESE with modes at either end of the range. This is illustrated in Fig. 5 which depicts small-scale fold axes of the eastern portion of the study area (Fig. 5a) and large-scale fold hinges measured over the whole Otjosondu area (Fig. 5b). The ENE mode corresponds with the D_2 structural grain, whereas the ESE mode represents the D_1 fold trend.

The Otjosondu area exhibits several styles in the superposition of D_2 structures on D_1 structures. This can be shown from the relationship of the s_2 fabric to pre-existing folds. Fig. 6 illustrates the poles to bedding in several areas investigated. The Otjosondu Kop (Fig. 6a) shows refolding of recumbent D_1 structures and a resulting ENE trend of the poles to bedding, whereas in Ann mine (Fig. 6b) the considerable dispersion of poles is caused by the D_3 refolding. At Dale mine (Fig. 6c), an east-trending primary D_1 fold has been partly rotated into the D_2 stress field as indicated by the clearly transgressive nature of the s_2 fabric. This fabric also cross-cuts structures at Eric mine (Fig. 6d). Further to the south, the Okonjete Hill antiform shows an ENE orientation conforming to the D_2 trend. Data in Fig. 7, however, elucidate a folding event chronology. An s_2 fabric crosscuts the Okonjete antiform and shows that

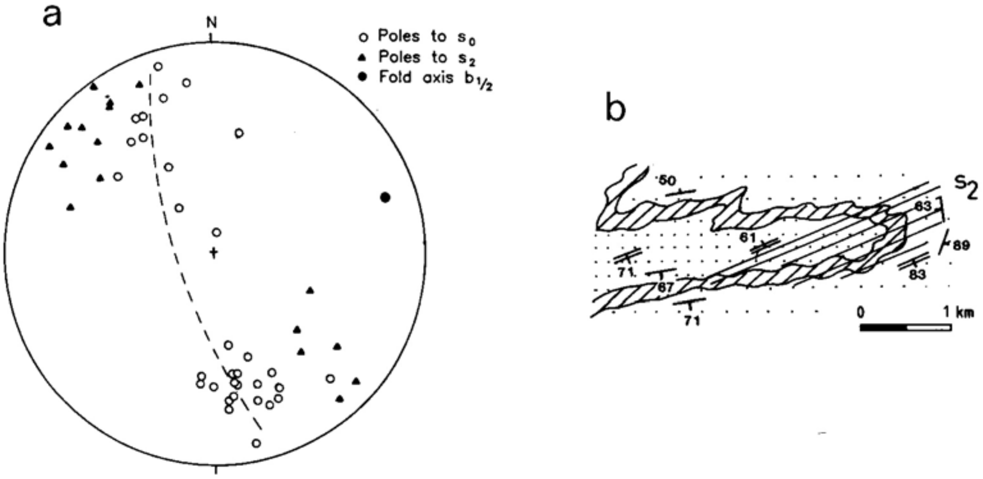


Fig. 7: Relationship between s_0 and s_2 at Okonjete Hill. The s_2 cleavage clearly cross-cuts the rotated D_1 fold as seen from the stereonet plot (a) and the geological map (b). Single lines are bedding, double lines are s_2 readings.

this structure had already been formed during the D_1 phase and was then rotated into parallelism with D_2 fold structures. These different patterns of superposed folding, namely classic mushroom-type interference patterns on one hand and subsequent rotation of previous structures into the D_2 stress field on the other, can be attributed to the polyharmonic nature of the D_1 fold style.

D_3 deformation and interference patterns

Folds of this event occur mainly on a medium to large scale. The folds are mostly open with their axial planes being upright to slightly inclined. At Otjosondu Kop, refolding of pre-D_3 structures can be observed and the D_3 axial trends are indicated in Fig. 4. In the same region, Ann mine displays a dispersion of poles to bedding due to this late folding event (Fig. 6b). The same dispersion due to D_3 refolding can be recognized at Eric mine (Fig. 6d) with D_3 fold axes plunging 25-40° towards the NNW. The interference between this event and earlier fold generations is approximately orthogonal, producing distorted basin-and-dome patterns of type 1 (Ramsay & Huber, 1987).

Brittle deformation

Several sets of late joints have developed in mostly quartzitic lithologies. Two sets of narrow brittle fracture zones have been observed particulary in the Lower Quartzites throughout the Otjosondu mining area. This is a conjugate set of sinistral and dextral fractures showing strikeslip movement. The sinistral set is predominant with an average Y-shear plane orientation of 350/82°E; the dextral set has an average Y-shear 'plane orientation of 317/86°E. Within these fracture zones, subvertical Riedel and Riedel conjugate shears are well developed, a feature which led Roper (1959) to refer to them as 'sawtooth joints'. Horizontal stress-release fractures occur as a closely spaced fracture cleavage predominantly in quartzitic lithologies. These cracks can only be observed close to the manganese ore horizons where they have been filled with mobilized haematite.

Discussion and Conclusion

A viable model to explain the reorientation of D_1 folds by a D_2 phase of folding and resultant fold hinge variability has been proposed by Odonne & Vialon (1987). Any degree of D_2 reorientation of D_1 folds may occur depending on the angle between the later shortening direction and the earlier fold trend, and this controls the heterogeneity of fold morphologies. Fold hinges of open, upright folds migrate from their earlier trends to be oriented in the later stress field provided these trends have a 40-60° angular difference, as is the case between D_1 and D_2 in the Otjosondu mining area. On the other hand, D_1 folds preserve their original trend if they are tight, upright F_1 folds which could not be tightened further and be reactivated during D_2. Inclined to recumbent F_1 structures experienced classic superposition, leading to crescentic interference patterns such as those at Otjosondu Kop (Fig. 4). Thus, the reason for the differing kinds of superposed folding originates from the diversity of D_1 fold styles summarized in Fig. 3. In contrast to this, the orthogonal superposition of D_3 on pre-existing fold generations has led to dome-and-basin interference patterns on a large scale.

Correlation of the D_3 and D_2 phases with deformation phases elsewhere in the Central Zone is relatively straightforward. Like other D_2 folds in the southern Central Zone, D_2 folds at Otjosondu mostly have their axial planes dipping towards the SSE, thereby indicating a NNW vergence. The D_1 phase at Otjosondu is correlated with less easily identifiable F_1 folds described by other authors in the southern Central Zone (Blaine, 1977; Sawyer, 1981; Downing & Coward, 1981). In these cases, the folds are recumbent and, as at Otjosondu, verge towards the northwest and east.

Compared with the western portions of the southern Central Zone, the less intense D_3 deformation phase at Otjosondu allows one to look through related structures at previous fold generations. DJ folds elsewhere in the southern Central Zone have been described as recumbent in attitude (Blaine, 1977; Downing & Coward, 1981; Sawyer, 1981) because they can only be identified where classic fold superposition has occurred. This study shows that D_1 folds may have been reactivated during the D_2 event and that their original nature may often have been obliterated. Together with the vergences recorded elsewhere in the southern Central Zone, an arcuate spread from the northwest towards the east is recorded for the vergence of D_1 structures.

Acknowledgements

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