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 these two generations. The superposition of D<sub>2</sub> folds on recumbent D<sub>1</sub> folds led to the development of dome-crescent mushroom interference patterns. In contrast, depending on the interlimb angle of upright D<sub>1</sub> fold morphologies, these D<sub>1</sub> folds either preserved their original D<sub>1</sub> trend or have been reactivated and reorientated to differing extents by fold hinge migration during D<sub>2</sub> deformation. The orthogonal superposition of D<sub>1</sub> warping on D<sub>2</sub> 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<sub>1</sub> and D<sub>2</sub> folds are correlated with obvious fold patterns developed throughout the Central Zone. The D<sub>3</sub> phase has only been recognized close to the Okahandja Lineament. Elsewhere in the inland branch this reactivation of D<sub>1</sub> folds by the D<sub>2</sub> deformation phase may explain why the identification of D<sub>1</sub> folds has been difficult.
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 \( F_3 \) folds. The reasons for this will be outlined after the successive fold generations have been described.

\( D_3 \) deformation

The \( D_3 \) deformation has produced folds on all scales ranging from centimetres to kilometres in wavelength. Upright, open and tight, recumbent \( D_3 \) 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. 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.

Fig. 3: \( D_3 \) polyharmonic folding in the study area. Overturned to recumbent NNE-verging folds as well as upright folds (open or tight) are illustrated.
sulted in polyharmonic fold styles (Fig. 3). This diversity in D₁ fold morphologies is important for understanding the mechanism of D₂ superposition discussed later.

An oblate quartz crystal shape fabric defines a planar s₁ foliation and, locally, well-oriented apatite inclusions mimic this fabric within coarsely recrystallized quartz grains. This fabric is particularly well developed in pelitic and quartzitic lithologies. A prominent l₁ lineation, produced by the intersection of cleavage with bedding planes, parallels the D₁ fold axes. The orientation of the D₁ 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 D₁ folds face towards the NNE, indicating a vergence in this direction.

**D₂ deformation**

D₂ 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 D₂ deformation is best revealed at Otjosondu Kop (Fig. 4), where the refolding of recumbent D₁ folds into a superposed D₂ syncline creates upward- and downward-facing synforms with respect to the D₂ fold axis. This large-scale isoclinal D₂ fold plunges moderately to the ENE. On a smaller scale, isoclinal refolding of D₁ folds by the D₂ phase can be recognized where contrasting competencies of quartzitic layers and haematitic quartzites are interlayered. The s₂ planar element in quartzites is defined by an oblate shape fabric of the quartz grains. This represents a subsequent coarse recrystallization, and the original s₂ cleavage planes have been modified and partly obliterated.

**Superposition of D₂ on D₁**

Pre-D₂ 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 ESE mode corresponds with the D₂ structural grain, whereas the ESE mode represents the D₁ fold trend.

The Otjosondu area exhibits several styles in the superposition of D₂ structures on D₁ structures. This can be shown from the relationship of the s₂ 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 D₁ 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 D₃ refolding. At Dale mine (Fig. 6c), an east-trending primary D₁ fold has been partly rotated into the D₂ stress field as indicated by the clearly transgressive nature of the s₂ 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 D₂ trend. Data in Fig. 7, however, elucidate a folding event chronology. An s₂ fabric crosscuts the Okonjete antiform and shows that
this structure had already been formed during the D₁ phase and was then rotated into parallelism with D₂ 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 D₂ stress field on the other, can be attributed to the polyharmonic nature of the D₁ fold style.

**D₃ 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-D₂ structures can be observed and the D₃ 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 D₃ refolding can be recognized at Eric mine (Fig. 6d) with D₃ 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 particularly 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 D₁ folds by a D₂ phase of folding and resultant fold hinge variability has been proposed by Odonne & Vialon (1987). Any degree of D₂ reorientation of D₁ 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 D₁ and D₂ in the Otjosondu mining area. On the other hand, D₁ folds preserve their original trend if they are tight, upright F₁ folds which could not be tightened further and be reactivated during D₂. Inclined to recumbent F₁ 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 D₁ fold styles summarized in Fig. 3. In contrast to this, the orthogonal superposition of D₂ on pre-existing fold generations has led to dome-and-basin interference patterns on a large scale.

Correlation of the D₁ and D₂ phases with deformation phases elsewhere in the Central Zone is relatively straightforward. Like other D₂ folds in the southern Central Zone, D₂ folds at Otjosondu mostly have their axial planes dipping towards the SSE, thereby indicating a NNW vergence. The D₂ phase at Otjosondu is correlated with less easily identifiable F₁ folds described by other authors in the southern Central Zone (Blaine,
Multiple deformation patterns in the Otjosondu area

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 D3 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 DJ folds may have been reactivated during the D2 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 DJ structures.

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