Saline horizons acting as thrust planes along the southern margin of the Damara Orogen (Namibia/SW-Africa)

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SUMMARY: At the S margin and at the base of the Naukluft Nappes of the late Proterozoic-early Palaeozoic Damara Orogen in Namibia so-called 'Unconformity Dolomites' are developed along thrust planes of nappes and within imbricate structures. Micro-probe analyses, phase-petrological relationships of the unusual mineral composition of the 'Dolomite', the salinity and composition of fluid inclusions as well as other geochemical data prove a saline origin of the 'Unconformity Dolomite'. These data combined with observations on the relationship of deformation and mineral growth, calculated geothermal gradients and radiometric datings lead to the conception that the 'Unconformity Dolomite' is a hot saline intrusion which has already intruded a pre-existing nappe pile. After intrusion and rapid crystallization, the rocks directly below the rigid dolomite plate acted as a thrust plane for last nappe movements which brought the Naukluft Nappes into their present position.

The 'Sonderforschungsbereich 48, University of Göttingen' is studying the geosynclinal and orogenic development of the intracratonic branch of the Damara mobile belt which forms part of the late Precambrian–early Palaeozoic Pan-African belt system. This paper deals with a rock type, known as 'Unconformity Dolomite' which, strata-like, forms the basal parts of the Naukluft Nappes and occurs widespread within thrusts and faults of the Damara Orogen. Therefore, this rock type seems to be of great importance from a tectonic point of view for a geodynamic interpretation of the Damara Orogen.

Geological setting

The extent of the area investigated is marked in Fig. 1 by black lines. The area includes the platform sediments of the Nama basin, the sedimentary rocks of the Naukluft Nappes overlying Nama beds in the N part of the Nama basin and the orthogeosynclinal sediments of the S Damara belt, including the sediments of the Kamtsas and Duruchaus Formation of the Nosib Group. In addition, to illustrate the geological position of the Naukluft nappes, the isolines of illite-crystallinity in the Nama Group (after Ahrendt *et al.* 1977) and the regional distribution of isograds in the Damara Orogen (after Hoffer unpubl.) are drawn on Fig. 1 (illite-crystallinity increases with decreasing values).

The 'Unconformity Dolomite'

Korn & Martin (1959) first mentioned a strata-like dolomite underlying the Naukluft Nappes and named it 'Unconformity Dolomite' (abbr. 'Udol') because of its unconformity with respect to the over and underlying series. They ascribed the dolomite to be sedimentary in origin, whereas Münch (1978) believed it to be a blastomylonite representing the lubrication layer of the Naukluft Nappes. As shown in Fig. 2, Münch took the view that the 'Udol' is built up in a bilaterally symmetrical manner with increasing cataclasis and recrystallization towards the centre. Before recrystallization, the core, therefore should have been composed of a very mobile suspension of ground dolomite saturated with liquid and gas phases, containing all mechanically reworked products of the series overridden by the nappe movement. Recent investigations on the mineral content, on fluid inclusions and on tectonic deformation, however, lead to a completely different interpretation of the genesis of the 'Udol'. The main results are summarized below. Detailed analytical data will be presented in another special publication.

Petrography

The main components of the 'Unconformity Dolomite' are stoichiometric dolomite, calcite and up to 35% of authigenic albite with a content of 0–5% anorthite. Therefore, petrographically, the 'Udol' can be best described as a siliceous albite-dolomite. In addition, more than 30 different minerals have been identified so far from inclusions of rock fragments and from the 'Udol', among which the high content of talc is striking. The prevailing part of all clastic inclusions in the dolomite matrix are cherts and albitites, not basement or nappe

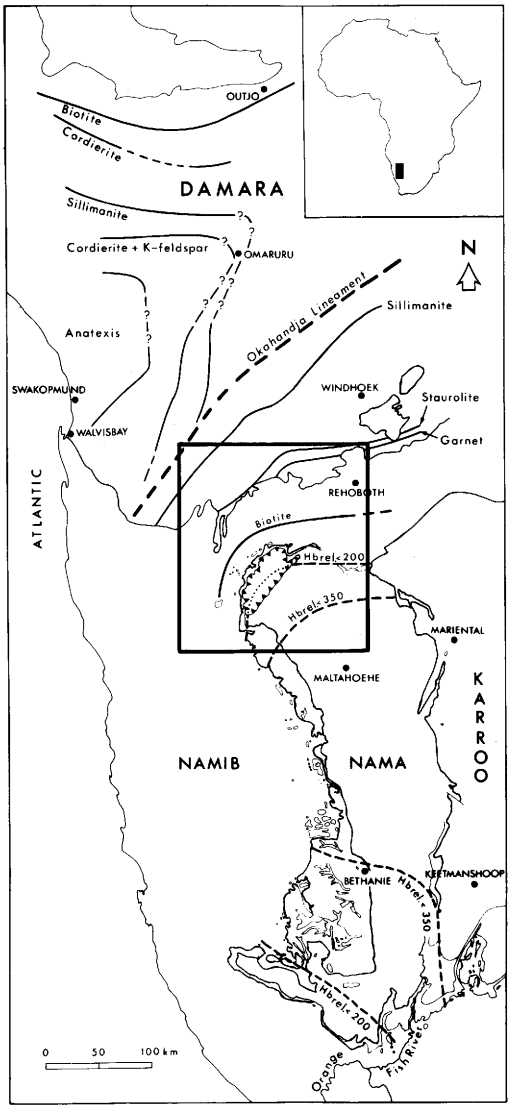

FIG. 1. Sketch map of the investigated area (heavy black line). Isolines of illite crystallinity in the Naukluft Nappes and in the Nama Group after Ahrendt *et al.* (1977), isograds in the Damara Orogen after Hoffer (unpubl.).

material. The content of boron-silicates, which mainly occur in cherts and albitites, is extraordinarily high; so far, tourmaline, dumortierite and danburite have been identified. Beside boron-silicates, the percentage of albite in these cherts can be so high, that one can find all transitions to pure albitites, which are exclusively built up of idiomorphic albites. The composition and structure point to 'Magadicherts', which originated diagenetically from Na-silicates such as magadiite or kenyaite. For the albitites, one can assume Na-carbonates and analcime-rich sediments as original material. The widespread distribution of Mg-riebeckite, which is found especially in the cherts, boron-silicates and crystalline rock inclusions is characteristic of the 'Udol'. The high Ti contents of tourmaline and Mg-riebeckite are unusual. Besides rutile, brookite was formed contemporaneously with Mg-riebeckite.

Fluid inclusions

In order to estimate the temperature of formation of the 'Udol' measurements on fluid inclusions were carried out. Tourmaline, Mg-riebeckite and, above all, albite and dolomite are extremely rich in 3- and 4-phase fluid inclusions of primary origin. The results of the measurements are shown in Figs 3 & 4. In all inclusions, there are halite crystals; the final melting-points of which indicate a salinity of the included solution of about 40% NaCl equivalents. The final melting-points of the ice lie in the positive range with a maximum between +5 and 10°C (see Fig. 3). That means that a small amount of CO_2 leads to formation of clathrates; CO_2-phases by themselves were not noticed. As shown in Fig. 3, the composition of the solutions and the homogenization temperatures change continuously from N to S. Beside NaCl in the N area, there are very often $CaCl_2$ crystals included which dissolve at between 450 and 480°C. In the S area, KCl crystals, which are dissolved at about 100°C before the homogenization of the gas phase, occur as second solid phase. As shown in Fig. 4, the minimum temperatures of formation of the 'Udol' decrease from 480–400°C to 320–280°C from N to S. The lithostatic pressure, at the time of mineralization, was determined in the N and in the S at about 700 bar; that means an overburden of about 2–3 km.

Discussion of the data

For a regional interpretation, the temperatures of formation were put into a figure of Ahrendt *et al.* (1977) showing values and isolines of illite crystallinity in the Naukluft area (Fig. 4) (NB: illite crystallinity increases with decreasing values). Temperatures and illite crystallinity decrease in the same way from N to S, but recrystallization in the 'Udol' and synkinematic recrystallization in the Naukluft Nappes and the underlying and adjoining Nama cannot be

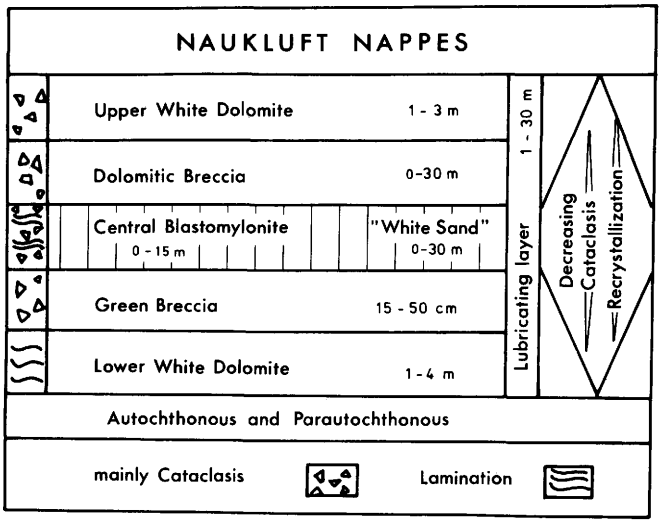

FIG. 2. Idealized standard profile of the Naukluft lubricating layer. In nature all five units are never present in a single profile (after Münch 1978).

of the same origin. While recrystallization in the Naukluft Nappes and in the Name beds caused by regional metamorphism shows a temperature of about 300–350°C and requires a depth of about 4–5 km, the recrystallization temperature of the 'Udol' is about 100–150°C higher (see Fig. 3) and it is recrystallized at a depth of only 2–3 km, as mentioned above. The higher temperatures for the formation of the 'Udol' would have required, if caused by regional metamorphism, a geothermal gradient of about 120–180°C/km. This is

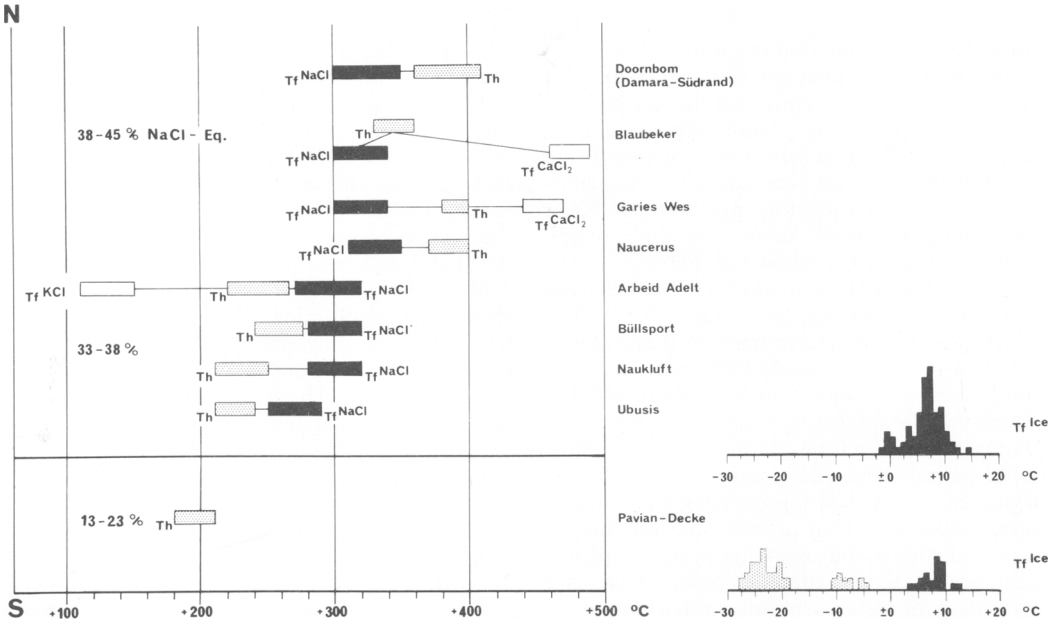

FIG. 3. Fluid inclusion measurements in the 'Unconformity Dolomite' and in the Naukluft Nappes. (Th: Temperature of homogenization; Tf: Temperature of crystal disappearance; Tf ice: Final melting point of ice).

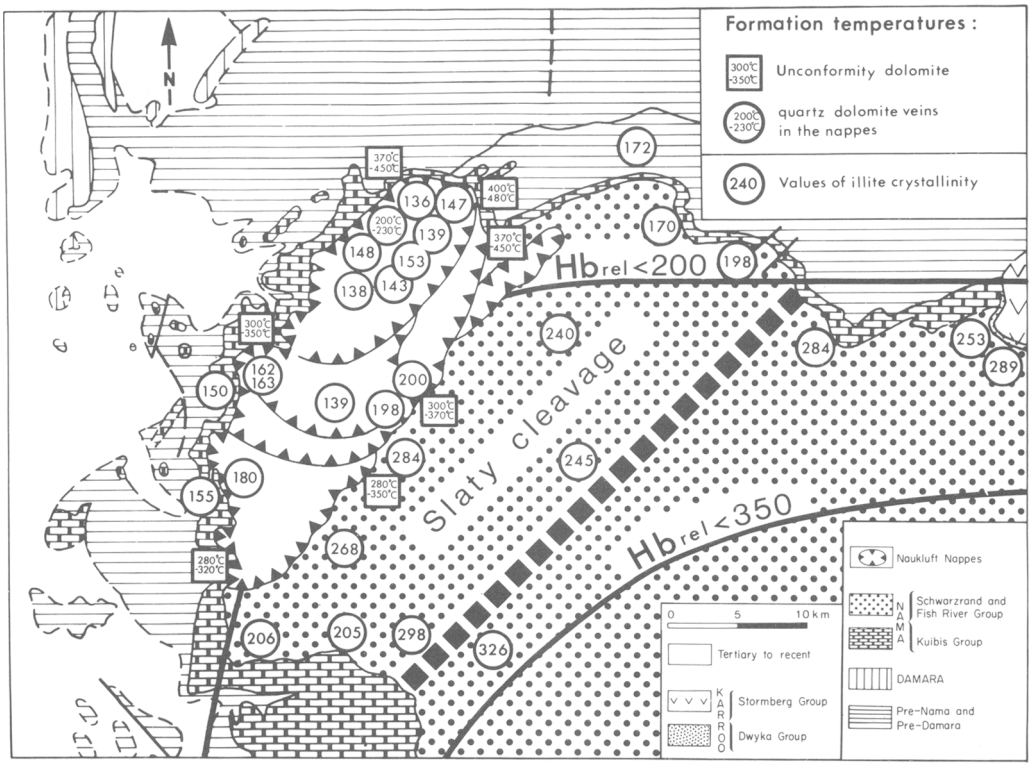

FIG. 4. Temperatures of formation of the 'Unconformity Dolomite'. Isolines and values of illite crystallinity after Ahrendt *et al.* (1977).

unlikely. An explanation of these high temperatures by friction heat can also be excluded if one postulates a highly mobile suspension (Münch 1978) for the 'Udol'. The geological situation of the 'Udol' becomes clearer if one additionally takes into consideration the temperatures of formation together with the K/Ar age determinations done in this region (Ahendt *et al.* 1977) shown in Fig. 5.

The synkinematic metamorphism in the Nama has a radiometric age of about 530 Ma. The same ages were found in parts of the southern Damara and in the Naukluft Nappes. In both units there are younger ages of about 495 Ma which may be interpreted as cooling ages or as dating a rejuvenation during post-crystalline deformation. The same age of 495 Ma was found in the 'Udol' representing the time of recrystallization. That is to say, at this time of recrystallization the overlying nappes and underlying series were already cooled down after their peak of metamorphism, so that the difference of temperature between the 'Udol' and the surrounding series was most probably in the range of 200–300°C. This difference of temperature together with the exotic mineral content of the 'Udol' can be best explained by a hot saline intrusion (see Fig. 6). After recrystallization, further tectonic shortening led to the formation of a thrust plane below the rigid dolomite plate. This overthrusting has mylonitizised the underlying series to a depth several metres without recrystallization so that the tectonic movements did not take place in the 'Udol' but below, in the underlying series. This can be proved by textural analyses which show a preferred mineral orientation resulting from tectonic movements in the underlying series, while the 'Udol' itself shows no preferred orientation. These last movements took place after regional metamorphism, because the isolines of illite crystallinity were cut off discordantly by the Naukluft Nappes (see Figs 4 & 5).

Conclusions

Cyclical, playa lake sediments with dolomite, sodium carbonates, sodium silicates and borates were the original material of the 'Udol' underlying the Naukluft Nappes. The basin of sedimentation was situated in the S graben zone of the Damara Trough (see also Martin &

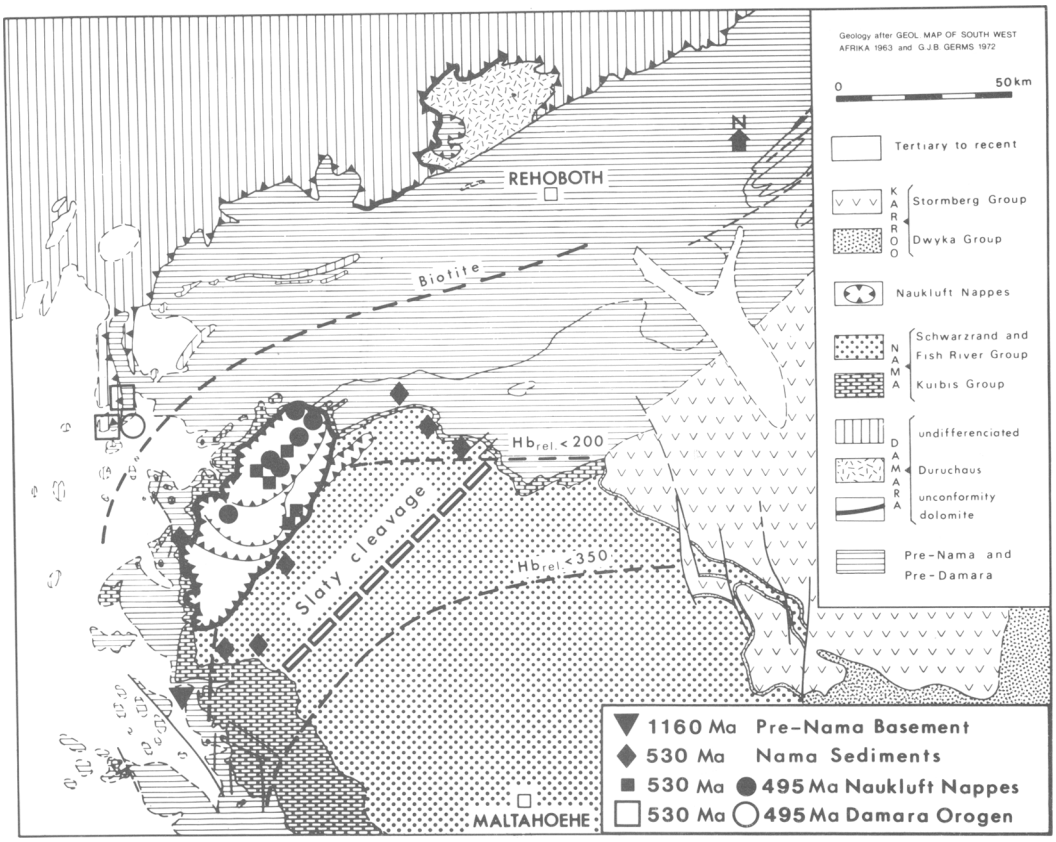

FIG. 5. K/Ar age determinations in the Naukluft area. In addition: Biotite isograd, isolines of illite crystallinity and southern boundary of slaty cleavage after Ahrendt *et al.* (1977).

Porada 1977). During a subfluence or an A-subduction, in the course of which the basement was transported to the N, parts of the saline sequence subjected to abnormally high pore pressure were squeezed out. The evaporite pulp intruded in nappe piles, thrust planes, fault zones and pocket-like, pipe-like and dyke-like into the over-and underlying series. The temperature of formation of the 'Udol' can be proved to be in the range of 380–480°C. Consequently, the temperature was 100–200°C higher than in the overlying nappes and the underlying autochthonous series during nappe movement. This is one of the main reasons why the 'Udol' is not regarded any longer as a lubricating layer but as a hot saline intrusion (For different interpretations of the 'Udol' compare Figs 2 & 6). Before crystallization took place, Mg-riebeckite was formed abundantly in connection with a Mg-Fe metasomatism. After intrusion and rapid crystallization, the rocks directly below the rigid dolomite plate acted as a thrust plane. During this time of post-crystalline deformation, the nappes of the Naukluft with their higher metamorphic grade were being pushed onto the lower metamorphic rocks of the Nama beds in the SE, discordantly cutting the isolines of synkinematic recrystallization in the underlying series, as shown in Figs 1, 4 & 5. The position of the biotite isograd of Damara metamorphism is important in determining the distance of transportation (see Figs 1 & 5) because we also find biotite in the higher metamorphic parts of the Naukluft Nappes, where the biotite has grown before nappe movement. Therefore, we can derive a minimum distance of transportation of about 50 km for the biotite-bearing parts of the nappes.

Rocks, similar petrologically to the 'Unconformity Dolomite' are to be found in similarly tectonic positions widespread at the S margin of the Damara Orogen (see the Duruchaus Formation on Fig. 5) and in the N of the orogen. These evaporitic sequences, which

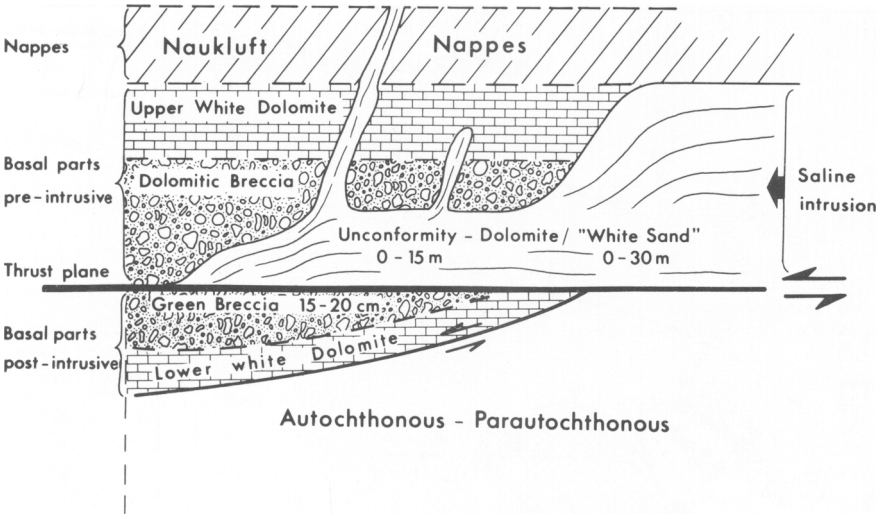

FIG. 6. Development of the basal parts of the Naukluft Nappes (Schematic section).

have not been noticed until now, must have covered large parts of the graben zones not only of the Damara but also of the other parts of the Pan-African belt.

ACKNOWLEDGMENTS. This work forms part of the research programme of the Sonderforschungsbereich 48 'Entwicklung, Bestand und Eigenschaften der Erdkruste, insbesondere der Geosynclinalräume', University of Göttingen (Federal Republic of Germany). Funds for this work were provided by the Deutsche Forschungsgemeinschaft (German Research Society). Thanks are due to Dr H.-G. Münch for some samples from the Naukluft area.

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