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Shear structures in anhydrite at the base of thrust sheets (Antalya, Southern Turkey)

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Abstract—Minor-scale structures in anhydrite layers and pods within one thrust contact of the Antalya Thrust System are described. Folds whose size range from some centimeters to several meters display a wide variety of attitudes. Their axes are curvilinear and vary from orthogonal to subparallel to the stretching lineation, leading to sheath folds and eyed type sections. Shear bands are frequent. In alternating white (pure) and brown (clay rich) anhydrite, regularly spaced extensional shear bands form typical tilted block patterns. In homogeneously foliated anhydrite they form isolated meter long extensional shear bands with brecciation along their central planes. Reverse-fault type shear bands are associated with meter scale reclined folds with axes subperpendicular to the stretching lineation. Normal and reverse fault type shear bands are self-exclusive, and both indicate a sense of shear toward the south at the scale of thrust system.

A model of progressive deformation of the anhydrite layers is presented. Anhydrite layers which have undergone a strong unstable shearing deformation along a thrust, have been boudinaged and now form elongate asymmetric pods. In thinned layers, normal extensional shear bands developed and recumbent fold axes are strongly reoriented toward the direction of the stretching lineation. In the thickened layers, reverse-fault type shear bands developed, particularly within the inverted limbs of asymmetric reclined folds whose axes are at a high angle to the stretching lineation.

INTRODUCTION

THE PURPOSE of this paper is to describe structures due to intense shear of evaporite units within the Antalya Thrust System in Southern Turkey (Fig. 1). These units are Early Triassic in age (Marcoux 1974) and consist of massive and foliated white anhydrite or alternating fine layers of white and brown (clay rich) anhydrite. Although most sedimentary rocks within the thrust sheets are only slightly deformed, the Triassic anhydrite is strongly deformed, demonstrating that shear during thrust sheet emplacement concentrated within these low strength layers. A wide variety of small-scale structures are observed: foliation, stretching lineation, shear bands, folds and boudinage. A common view of structures in such rocks is that they are chaotic, and therefore not related to the bulk deformation environment. The structures we observed on particular outcrops define a complex pattern, but one which is consistent with a progressive shearing history.

GEOLOGICAL SETTING

The Antalya Thrust System, on the southern coast of Turkey (Fig. 1) is a complex imbrication of thrust units made of platform deposits, slope deposits, radiolarites and ophiolites. The system is overthrust onto the Mesozoic and Cenozoic of the platform sequence of the Taurus Calcareous Axis (Ricou *et al.* 1975). Three major thrust units have been recognized (Delaune-Mayère *et al.* 1977, and Marcoux unpublished work), namely from bottom to top: (a) Lower nappes comprising slope deposits; (b) Median nappes of basin deposits and ophiolites; and (c) Upper nappes of platform and basin limestones (Marcoux 1979).

The structure of this thrust system is strongly non-cylindrical and the kinematics of emplacement cannot be simply inferred from the geometry of the fault pattern. Moreover, a controversy has arisen about a northward vs southward emplacement for this thrust system (see discussion by Ricou *et al.* 1985, Robertson & Dixon 1985, Şengör & Yilmaz 1981). The rocks within the thrust sheets are weakly deformed. Therefore, we have focused our study on the shear criteria near the basal sole of Lower, Median and Upper nappes. Anhydrite constitutes discontinuous layers a few meters thick along the major thrust fault, which brings the Upper nappes (here the Kemer Nappe) to rest upon the Median nappes (here the Alakir çay Nappe). This anhydrite derives from the early Triassic levels of the Alakir çay sequence. The present paper describes only those microstructures developed within anhydrite during shearing. For this purpose structures are described from two outcrops selected for their quality and accessibility (ANH1 and ANH2, located in Fig. 1), along the base of the Kemer thrust sheet, separated by 20 km. At both sites the anhydrite belongs to the Triassic levels of the underlying Alakir çay thrust sheet. ANH1 is near Beycik village along the Antalya Finike road (long. 30°27′; lat. 36°29′). ANH2 is located north of Kesme köprü (long. 30°29′; lat. 36°36′30″). The mean foliation is almost horizontal at ANH 1, and is sub-vertical at ANH 2 as a consequence either of late tilting without modification of internal

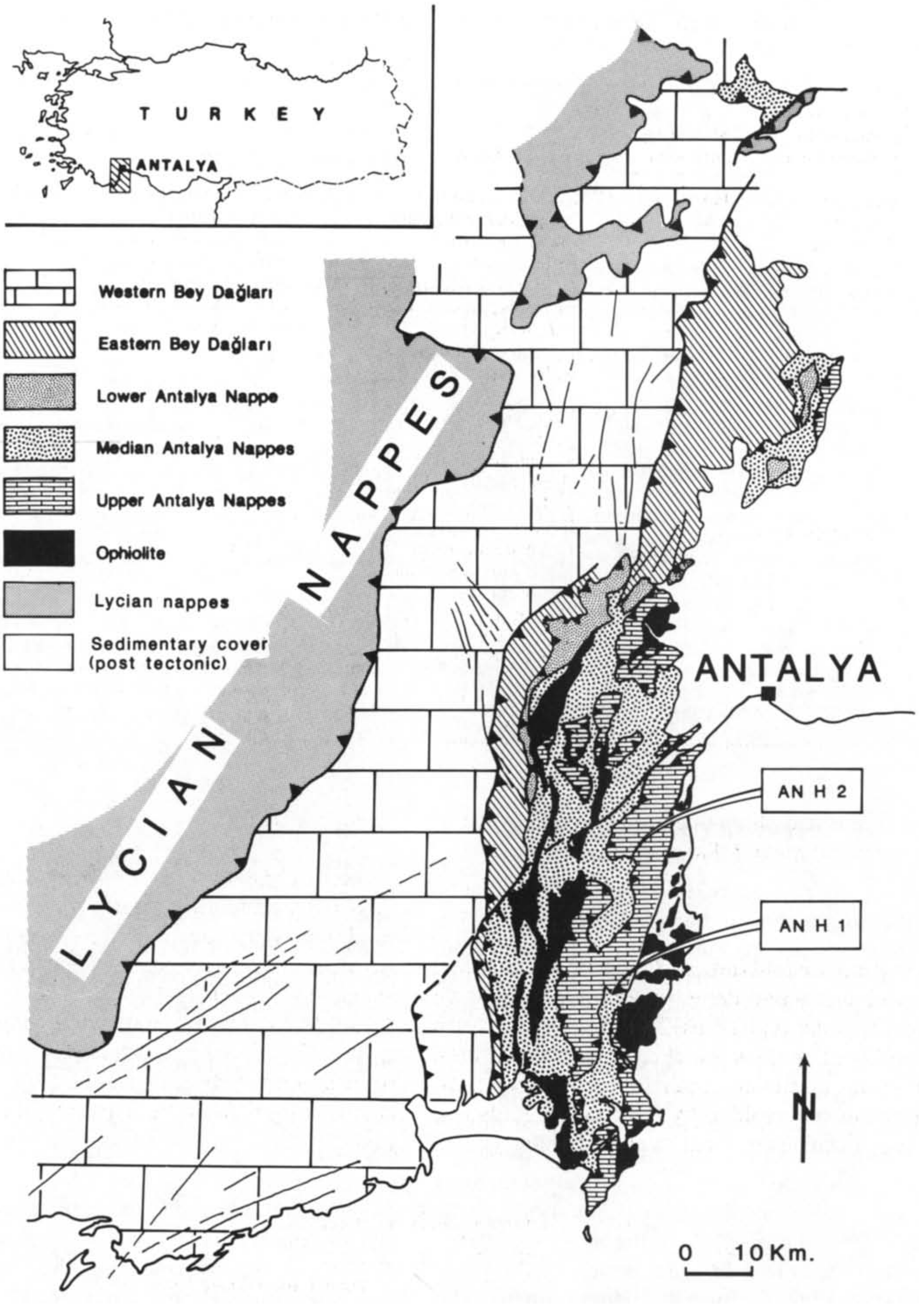


Fig. 1. Location map and structural sketch of the Antalya Thrust System, showing the two anhydrite localities (ANH1 and ANH2) studied.

structures or a lateral ramp. The various structures which can be observed on each site are listed in Table 1.

FOLIATION AND LINEATION

The anhydrite displays a strong foliation parallel to the bedding surfaces. In the following, the foliation plane S is taken as the $\lambda_1\lambda_2$ principal plane of the strain ellipsoid. A stretching lineation L is equated with the λ_1 direction of principal extension in the strain ellipsoid. L is defined by elongated nodules of coloured anhydrite, by grain elongation, and by preferred orientation of rigid inclusions. On bedding surfaces, the stretching lineation often parallels corrugation axes and local slikensides which indicate differential movement between anhydrite layers.

The small-scale structures described below will be oriented with respect to S and L.

FOLDS

A wide variety of fold orientations and shapes is observed (Table 1). Almost 80% of the fold axes are

Table 1. Types of structures observed on sites ANH1 and ANH2 (see locations in Fig. 1).

	Structures				
Studied outcrops	Foliation (S) Parallel to bedding plane	Stretching lineation L	Folds	Boudinage	Shear zones
ANH1	Flat lying. Parallel to bedding plane (Fig. 2)	Horizontal	(1) Isoclinal recumbent folds with axes parallel to L or sheath like; scale: cm–dm (2) Asymmetrical fold trains with axes perpendicular to L; scale: dm (3) Upright to reclined folds with axes parallel to L; scale: cm (4) Reclined folds with axes perpendicular to L associated with reverse shear zones (Fig. 4c); scale: m–dm	(1) Symmetric boudins of brown anhydrite interbedded with white anhydrite; scale: cm–dm (2) Asymmetric boudins separated by extensional shear zones; scale: cm–m	(1) Isolated extensional shear zones, sometimes with breccias in their centres (2) Regularly spaced extensional shear zones giving rise to tilted block pattern (3) Reversed fault type shear zone associated with reclined folds (Fig. 4c)
ANH2	Vertical-parallel	Gently plunging	(1) Isoclinal and upright (rotated recumbent folds) with axes parallel to L or sheath like (Fig. 4a & b); scale: cm–m (2) Asymmetrical fold trains with steeply plunging axes (3) Not observed (4) Not observed	(1) As above (2) As above	(1) As above (Fig. 5b & d) (2) As above (Fig. 5c) (3) Not observed

subparallel to the stretching lineation, L, whatever the axial planes dip and mean foliation attitude (Fig. 2).

Recumbent folds

The most common folds are isoclinal with axes parallel to L and axial planes parallel to foliation, S. Fold hinge profiles are of similar type (Class 2, Ramsay 1967). Such folds are observed on the scale of centimeters to several meters (Fig. 4a) and even larger folds probably exist. Minor folds can be refolded by later minor folds and undulations, or can be cross-cut by shear bands.

Sheath folds

Axes of sheath folds are generally parallel to L and their axial surfaces subparallel to S. They are several centimeters in size and are responsible for eye-like structures on sections perpendicular, or at high angle, to L (Fig. 4b). They are quite similar to sheath folds observed in metamorphic rocks (Quinquis *et al.* 1978; Cobbold & Quinquis 1980), and have also been described in salt (Talbot 1979). Some of the recumbent folds could be segments of larger scale sheath folds.

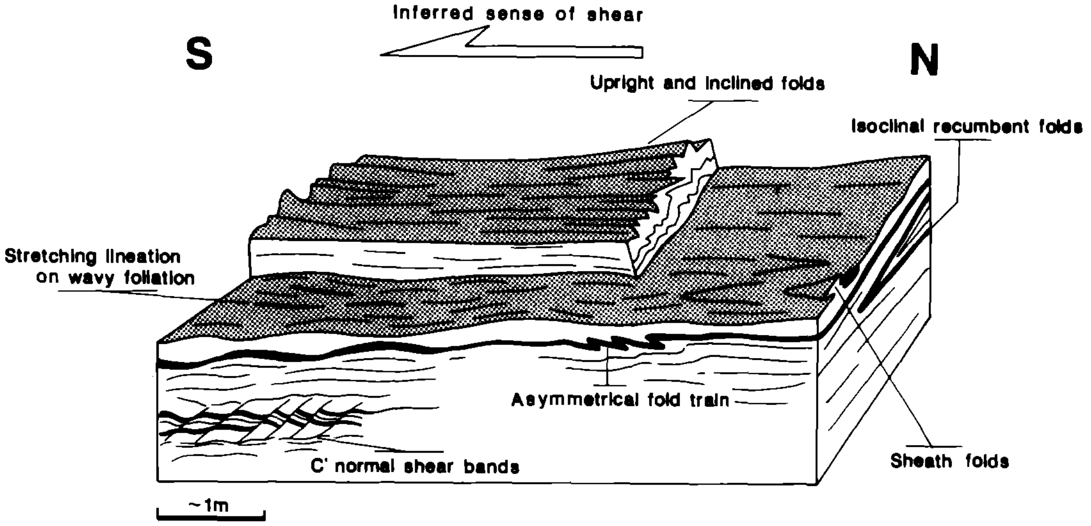


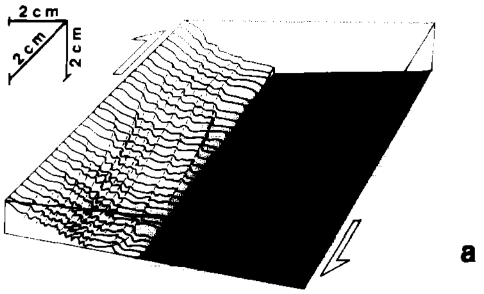
Fig. 2. Schematic block diagram illustrating the relationships between the different types of small-scale structures observed at ANH1 and ANH2 outcrops. (See locations in Fig. 1.)

Asymmetric fold trains

They occur in multilayers of brown and white anhydrite or where an isolated brown layer is embedded in a white matrix (Fig. 2). Fold axes are almost perpendicular to *L*. Fold profiles of brown layers range from parallel (Class 1B, Ramsay 1967) to similar (Class 2) but are commonly of intermediate type. As suggested by experiments (Ghosh 1966, Manz & Wickam 1978) and theory (Treagus 1973), these observations indicate that such folds initiate by buckling and have undergone further flattening during a shearing deformation. The vergence is in the same sense as the bulk sense of shear.

Upright to reclined folds with axes parallel to the stretching lineation

A peculiar type of folding is locally observed in banded anhydrite. Folds with 'en-chevron' profiles have their axes parallel to the stretching lineation, but display a large fan of axial plane dip (Fig. 3). The fold profile shapes do not indicate homogeneous strain superimposed on buckling, and there is no indication that axial-plane orientation is related to progressive deformation. It is probable that such folds initiated with axes close to parallel to the stretching lineation. Such a folding process has been obtained in simple shear experiments by Hugon (1982): the layers to be folded contained the shear direction but were initially oblique to the shear plane (Fig. 3a). However, the observed fold geometry could also indicate a shortening component along λ_2 (a constrictional strain history) due to local boundary conditions (Fig. 3b) (see Nicolas & Boudier 1975).



Simple shear (Layer initially oblique to shear plane)

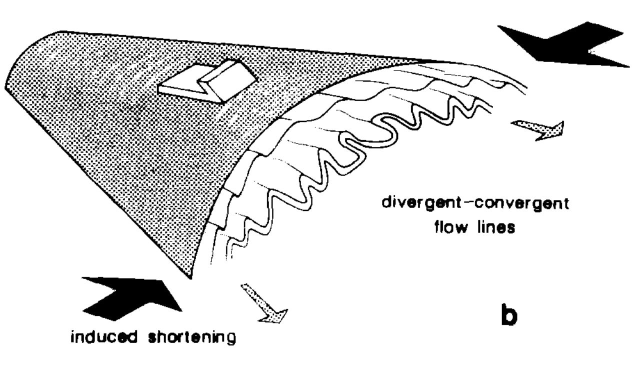


Fig. 3. Two possible models to explain the origin of upright to reclined folds with axes parallel to the stretching lineation. (a) Experimental model in simple shear in which the layer to be folded is originally oblique to the shear plane but contains the shear direction (after Hugon 1982). (b) Model of divergent–convergent flow near an irregular boundary.

SHEAR BANDS AND BOUDINAGE

Shear bands are very common from the centimeter to the meter scale. They are brittle or brittle–ductile (see Ramsay 1980, fig. 1) shear bands, according to the lithological nature of the anhydrite and the timing of their development. From a kinematic point of view it is more convenient to distinguish between normal fault type shear bands (extensional; *ecc* of Platt & Vissers 1980, and *C′* type of Berthé *et al.* 1979) and shear bands exhibiting a reverse sense of shear (contractional).

Extensional shear bands

Extensional shear bands in homogeneously foliated anhydrite formed at 10–30° to the foliation, *S* (Fig. 5). Centimeter-spaced shears are well developed within brown layers. Normal displacements along these shear bands are accommodated by ductile deformation in the adjacent layers of white anhydrite. A 10 cm shear band which cross-cuts the white–brown layering and terminates abruptly along a slightly curved but undisrupted layer of white anhydrite (Fig. 5b), suggests a strong rheological contrast between the pure (white) and impure (brown) anhydrite. In zones of intense deformation, the movement along shear bands is accommodated by cracks and gashes infilled by white anyhydrite (Fig. 5a). At the outcrop scale, these shear zones are characterized by breccias (Fig. 5d), with spaces between the brecciated blocks generally infilled by brown anhydrite.

Outcrops where layers of dominantly white anhydrite alternate with layers of white and brown banded anhydrite show particularly interesting structures. The white–brown layers display a typical tilted block pattern (Fig. 5c): the extensional shear bands are at a high angle (50–60°) to the original layering which is tilted by 20–30°. The darkest layers form boudins separated by white anhydrite veins. The neighbouring layers of dominantly white anhydrite exhibit shear bands which are commonly in conjugate sets (Fig. 5c). These differences in structures suggest a difference in rheology and strain history. The white anhydrite appears to be more ductile than brown anhydrite and able to accommodate the bulk deformation more continuously. White and brown layers thus partition strain differently (Lister & Williams 1983). Once initiated, shear bands in the competent brown layers allow an almost rigid rotation of individual blocks; the shear-induced vorticity is seemingly converted into spin. In the dominantly white layers, the deformation is achieved by combinations of continuous (ductile) and discontinuous (shear bands) deformation: here, shear-induced vorticity would seem to be partitioned into non-coaxial ductile deformation, and into spin to a lesser degree.

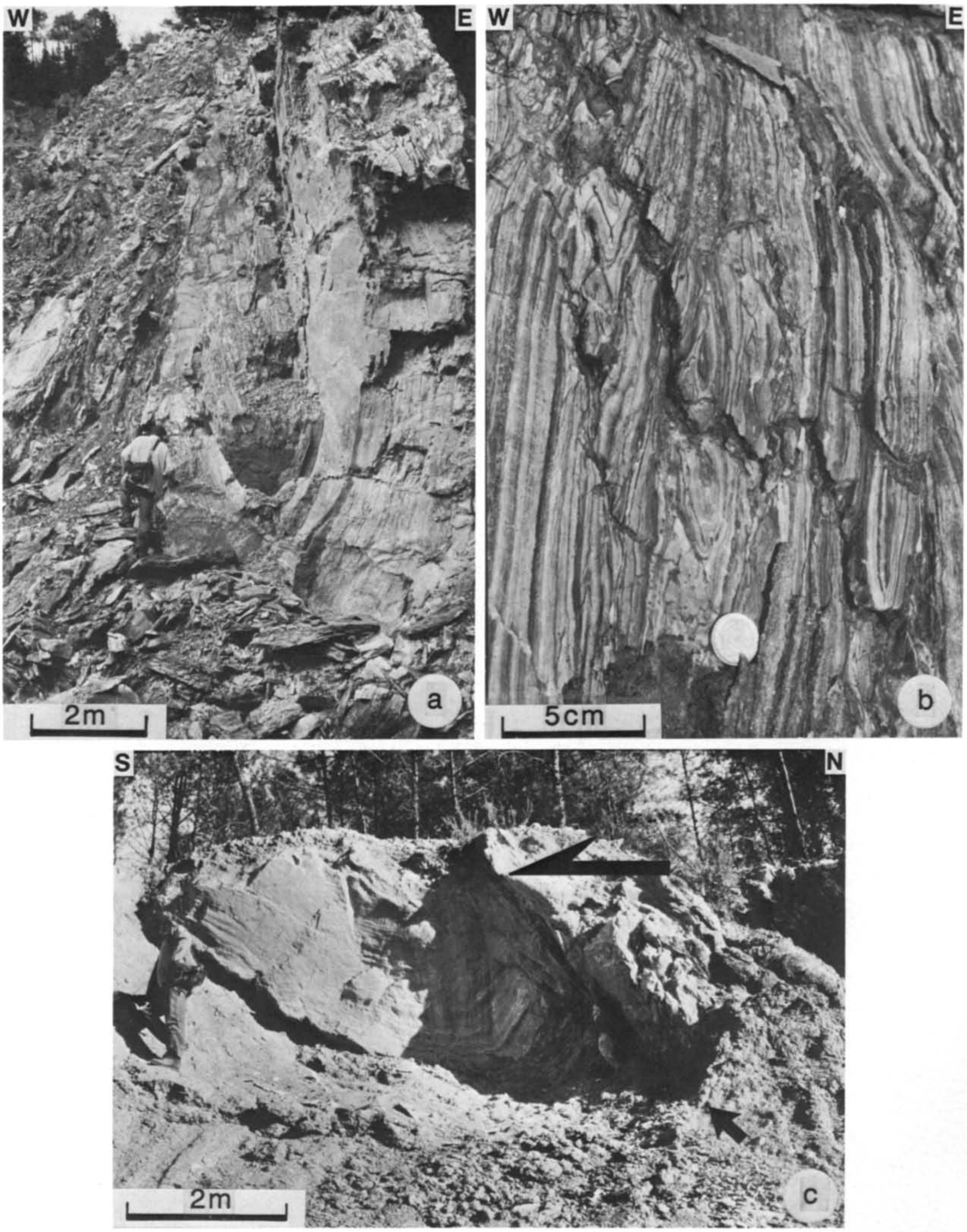


Fig. 4(a). Meter scale isoclinal fold originally recumbent and tilted to the vertical by late movements (ANH2). (b) Eye-like section of sheath folds (ANH2). (c) Reverse-fault type shear band (small arrow) associated with reclined fold (ANH1).

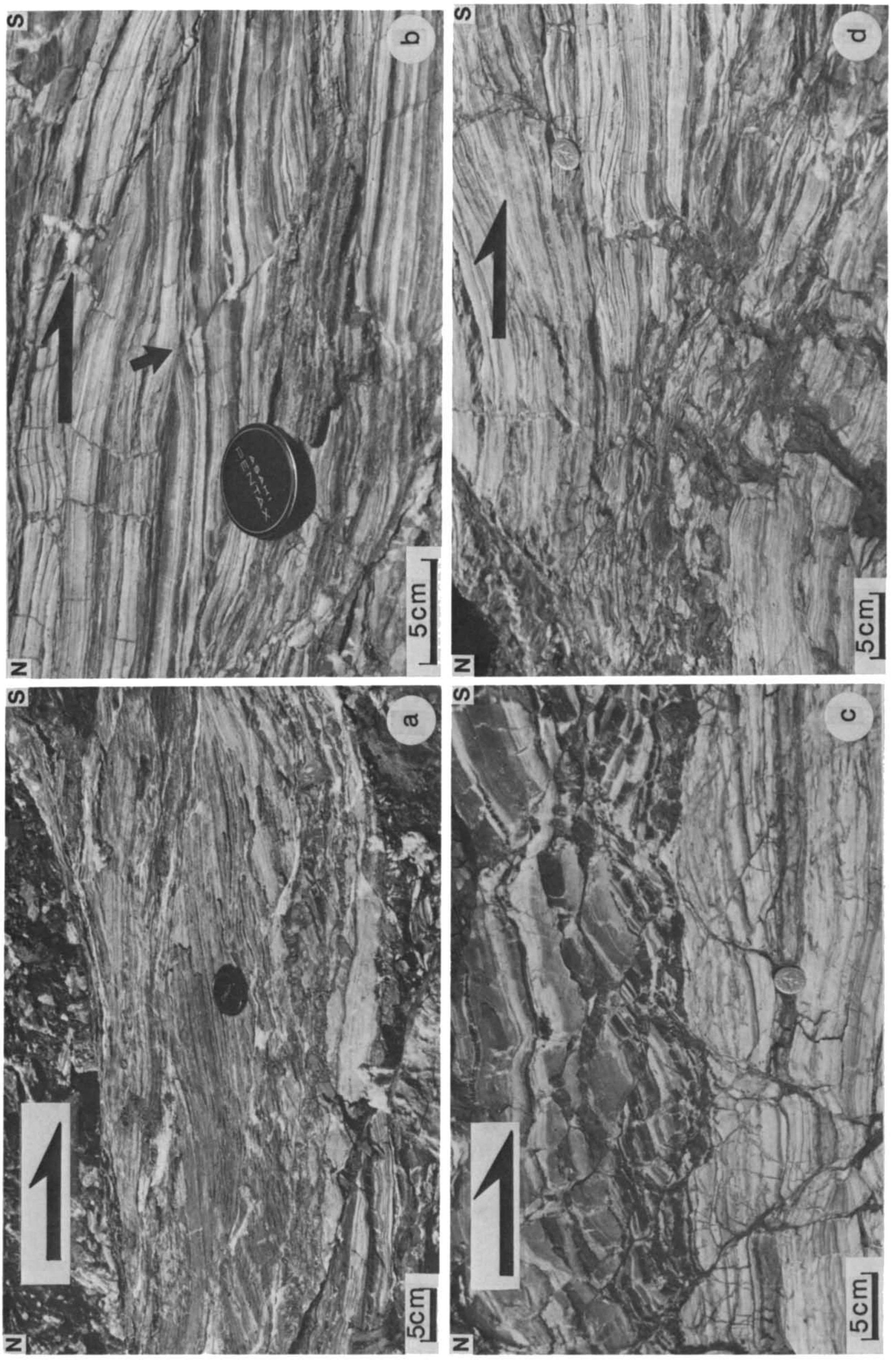


Fig. 5(a). Obliquity between foliation and shear bands associated with veins of white anhydrite (ANH2). (b) Isolated extensional shear band terminating along bedding parallel foliation (ANH2); the small arrow indicates the termination of shear band. (c) Tilted block pattern due to regularly spaced extensional shear bands. Note boudinage of dark layers and conjugated shear bands within the pale layer (ANH2). (d) Shear zone with brittle deformation in its center part. The large arrows indicate the sense of shear on all figures.

Reverse-fault type shear bands

Reverse shear bands occur only at the meter to decimeter scale, and are always associated with reclined folds whose axes are almost perpendicular to the stretching lineation (Fig. 4c). We believe they are late structures associated with local shortening of anhydrite layers.

CONCLUSIONS

(1) Deformation is concentrated in evaporitic layers involved in thrust tectonics. They are therefore powerful tools for deciphering the kinematics of thrust systems developed in the upper part of the crust. At the base of the Kemer unit in the Antalya Thrust System, the observed structures are consistent with a southwards thrusting.

(2) Even if the structures in anhydrite seem geometrically and spatially complex, they are neither disordered nor chaotic. They are, as in any other rock deformed ductilely, organized into coherent patterns with respect to principal axes of finite strain.

(3) Folds can develop with axes orthogonal or parallel to the stretching lineations. When initiated orthogonal to the lineation, fold axes can suffer large reorientations toward the stretching direction and result in sheath folds.

(4) Shear bands can be of normal sense (C' or extensional shear bands) indicating thinning of anhydrite layers or of reverse sense indicating thickening.

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