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INFRASTRUCTURE OF THE METAMORPHIC ROCKS IN SOUTH BULGARIA – DISCUSSION

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ABSTRACT. The infrastructure of the metamorphic rocks in South Bulgaria comprises strata involved in recumbent folding. It appears very difficult to distinguish alpine recumbent folds from pre-alpine recumbent folds. Apparently the recumbent folds have been refolded at different time, however because of lack of reliable structural geological investigations the fold generations are not systematized. In addition to the folding problem, very conspicuously a problem with the interpretation of the lineations and other minor structures exist. In Bulgaria the lineation is used as a powerful criterion for solving problems of time and space, such as separation of lithotectonic units (e.g. Ardinska and Asenishka units in the Rhodopes). In reality studying of the stretching lineation is not new and universal method. In Bulgaria stretching lineations, parallel to the axes of the folds, is measured as a rule. However, only in very isolated case, when the folds are true sheath folds formed by extreme shear, the stretching lineation is really parallel to the axes of the folds. In most cases, the stretching lineation is perpendicular to the axes of the folds. It is not sure at all that most of the folds in the Rhodopes are sheath folds. Even if lineation parallel to the axes of the folds is measured, it is not parallel to the direction of tectonic transport. The direction of tectonic transport usually corresponds to the direction of regional shortening, which is perpendicular to the fold axes. Lots of evidences are available that the lineation in the Rhodopes is of many different types and that old reworked lineations are frequently encountered.

ИНФРАСТРАКТУРА НА МЕТАМОРФНИТЕ СКАЛИ ОТ ЮЖНА БЪЛГАРИЯ - ДИСКУСИЯ

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РЕЗЮМЕ. Инфраструктурата на метаморфните скали от Южна България се формира от скалите, засегнати от лежащи гънки. Оказва се много трудно да бъдат разграничени алпийски лежащи гънки от доалпийски лежащи гънки. Очевидно лежащите гънки са пренагънати в различно време, но поради липса на надеждни структурно-геоложки изследвания гънковите генерации не са систематизирани. В допълнение на проблема с гънките съвсем очебийно се налага проблема с интерпретацията на линейността и други дребни структури. Линейността в България се използва като могъщ критерий, чрез който се решават въпроси за пространство и време, като например отделянето на литотектонски единици (Ардинска и Асенишка единици в Родопите и др.). В действителност изучаването на линейността на разтягане изобщо не е нова и универсална методика. У нас като правило се мери линейност на разтяганер паралелна на осите на гънките. Обаче само в много изолираните случаи, когато е проявен един специален тип гънки на срязване – ножични гънки, формирани при екстремално срязване, линейността наистина може да бъде паралелна на осите им. В повечето случаи тя е перпендикулярна на осите на гънките. Изобщо не е сигурно, че повечето от гънките в Родопите са гънки на срязване, а още по-малко ножични гънки. Даже и да се измери линейност паралелна на осите на гънките, това не означава, че тя е паралелна на посоката на тектонски транспорт. Напротив, посоката на тектонски транпорт почти винаги съответства на посоката на регионално свиване, която е перпендикулярна на осите на гънките. От друга страна, налице са много доказателства, че линейността в Родопите е от най-различни типове и че се срещат стари и пренагънати линейности.

Infrastructure description

The text below is focused predominantly on the infrastructure of the Rhodopes with minor reference to the infrastructure of the Strandja-Sakar Zone (SZ) in South-East Bulgaria. The main assumptions and models used for academic description of Rhodope are examined critically with the aim of provoking discussion on some unresolved or ignored problems.

Folds or thrusts?

It is very significant if the flat-lying structures in transposed terrain such as the Rhodope or Strandja-Sakar zone (SZ) are recumbent folds, thrusts or nappes (Fig. 1a). If they are recumbent folds, then the younging directions are inverted, while in the nappe sheets the beds may be facing normally. For the creation of its geological map of the central Rhodope D. Kozoukharov (e.g. Kozoukharov, 1965; Kozoukharov, 1968, unpublished Ph.D. theses; Kozoukharov, 1984) assumed that there is not large recumbent folds and significant thrust displacements, which would interfere with the stratigraphic superposition. This allowed him to elaborate on a lithostratigraphic scheme, which was later used in one or another way by all authors. The proponents of the nappe tectonics in Rhodope (e.g. Ivanov et al., 1984; Ivanov et al., 1985) also assumed that normal superposition is preserved in the nappes.

If recumbent folds dominate, the source rocks can be considered locally derived, because the same strata repeat in the sequence. If large nappes are present, large tectonic transport may have taken place, such as one involving transportation from hundreds of kilometers, as it was suggested for the Rhodopes (e.g. Burg et al., 1990, Burg et al., 1996a, 1996b; Dimov et al., 2000). However, in this case the rock strata in the tectonostratigraphic units proposed in the nappe model for the Rhodopes would be alien to each other, because rocks from different source areas are involved. So far, the existence of significant recumbent folds in Rhodope has been rejected or ignored by all main researchers. The reasons for that are pretty obvious. If such folds exist, the superposition is not normal and lithostratigraphy can be made only by very detailed correlations and structural analysis in which possible repetition of strata is accounted. If recumbent folds exist, then the thrust models assuming large displacement and the tectonostratigraphic subdivision based on it will not be correct. The simple compression–extension sequence of deformation events (the metamorphic core complex) also would not be correct in many of its assumptions. However, there is one small problem! In detailed study alternation of "S" and "Z" geometry of small folds (Fig. 1b) will be encountered and mesoscopic refolded recumbent folds will be observed. A researcher will find numerous folds with shallowly dipping axial planes (Fig. 1c-d), and suspicious repetitions of lithology uphill. Similar to the Rhodope is the situation in the SZ, where recumbent folds are also present. The shallowly dipping structures in the SZ are usually interpreted as thrusts, however cleavage bedding relationship for inverted fold limbs are most frequent. In some rare cases, large recumbent folds are proven in the SZ by detailed structural studies combined with drilling that uncovered inverted stratigraphy (e.g. Maliakov, 1976).

Are the thrusts in Rhodope sinmetamorphic?

It is commonly stated that the thrusts in the Rhodopes are synmetamorphic (e.g. Dimov, 1994; Burg et al., 1996a). The natural questions to ask are: Is there only one regional metamorphism, and only one generation of thrusts, and if not to which metamorphism the thrusts are synmetamorphic? The tectonic model for the Rhodopes, which dominates at present (e.g. Burg et al., 1996b; Dimov et al., 2000; Bonev et al., 2006) is based on the assumption, that the thrusts are synmetamorphic to an alpine metamorphism. Basic field observations suggest that this idea is oversimplification (e.g. Zagortchev, 1994; Dimitrov, 2001). It is easy to spot, that the structure is too complex (Fig. 2a,b) in order to be formed only in one orogenic cycle, and in many ways the Rhodopes are similar to the other old massifs in Europe, which have pre-alpine Variscan and Caledonian imprints. Why should the Rhodopes be different? Secondly, numerous exposures show overprinting relationships of postmetamorphic thrusting (Fig. 2b). On Fig. 2 the aplites are cutting early high-grade metamorphic foliation. That suggests, that thrusting may be synchronous to the aplite injection, but not to the high-grade metamorphic foliation, which was folded and sheared prior to the aplites. At best, the thrusts are synchronous to lower grade "diaphthoresis", which is superimposed on most of the high-grade rocks in the Rhodopes and is described in numerous texts. On the other hand, some transposed folds, have hinges, that are overprinted by high-grade foliations. In all cases, alpine and pre-alpine structures have to be recognized.

Structural geological controversies of the Rhodopian infrastructure

On of the most frequently encountered statements about the Rhodopes is that stretching lineation is abundant, and "stretching lineation is parallel to the axes of the folds and to the direction of tectonic transport". Consequently, based on this assumption, the Central Rhodope is divided into major tectonostratigraphic units (e.g. Ardinska unit and Asenishka unit), which differ in direction of tectonic transport, found by the orientation of the stretching lineation (e.g. Dimov, 1994; Dimov et al., 2000). However, the assumption, that tectonic transport is parallel to the axes of folds, is very controversial from structural geological point of view and will be addressed in the text below.

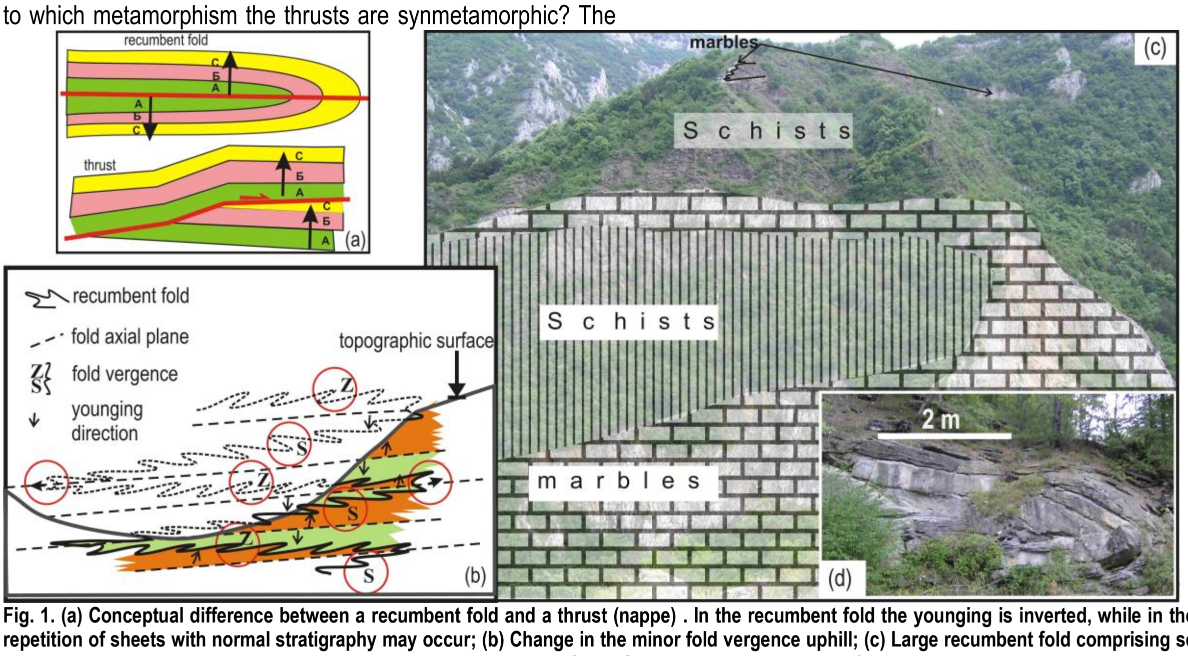

Fig. 1. (a) Conceptual difference between a recumbent fold and a thrust (nappe) . In the recumbent fold the younging is inverted, while in the nappe pile repetition of sheets with normal stratigraphy may occur; (b) Change in the minor fold vergence uphill; (c) Large recumbent fold comprising schists in the core and marbles in the limbs observed in the eastern slope of the Chepelarska river, south of Asenvgrad. The observation section is oriented approximately north-south; (d) Recumbent fold closure (high-grade foliation is folded in the hinge; the fold's axial surface participates in gentle F_2r-F_3r dome; the exposure is located south of Rojen)

Pseudo-structures in Rhodope

Pseudo-sheath folds

Extreme shear gradients are suggested for the Rhodopes (e.g. Burg et al. 1990; Burg et al., 1996a,b; Dimov, 1994; Gerdjicov, 2004), which were unraveled by kinematics analysis. However, true sheath folds in the sense of Cobbold and Quinquis (1980) are rarely encountered in the Rhodopes. They are vaguely mentioned in the texts of the papers (e.g. Burg et al., 1996a) and not shown on photographs or subjected to orientation or shape analysis. The personal observations of the author show, that most of the candidates for sheath folds are in fact flattened or conical interference forms produced by superposition of upright folds on recumbent folds. Such interference forms of course can not be used for kinematics analysis. Since proper descriptions of sheath folds in the regional literature are missing, it is impossible to confirm or reject the suspicion that sheath folds are rare or not present at all. The “pseudo–sheath” folds are observed mainly in vertical cross sections. They are varieties of “basin and dome” or ”egg-carton” interference pattern. The key for formation of this interference pattern is the existence of transposed folds with shallowly dipping axial surfaces, which were refolded in later deformation events.

Pseudo-detachment surfaces

Indeed there are shear surfaces separating the marbles of the variegated upper complex from the granite-gneisses of the lower complex (here lower and upper are used in the sense of (Kozoukharov, 1984). These shear surfaces were located on the sheets of the geological map of Bulgaria in scale 1:100000 and on previous reports and publications as thrusts, normal faults or “nadseds” (reverse faults). In reality, it is natural to expect shear on the contact between marbles and granitic gneisses. It is also natural to expect shear in the limbs of flexural slip folds, where strata of different lithology are folded. Indeed, the post-metamorphic upright folds of the suprastructure, that refolded the transposed strata, are flexural slip folds. The slip in the limbs of these folds is marked by slickenside striation. Locally, this slip may evolve into brittle-ductile shear zones of limited displacement. At present, some shears are shallowly dipping and qualify for detachment faults but others are steeply dipping. Even for the shallowly dipping shear surfaces it is not sure at all, that they have been originally formed as shallowly dipping (detachment) surfaces. It is likely, that they have been tilted to shallow dips after their initiation; because some shear surfaces are folded by later upright folds, and comply with the fold curvature. It is possible that these shears accommodated some extension, as the core complex model require, but the magnitude of extension, the original dip and the time, when they were first initiated is complete mystery.

Significance of the boudinage

In the texts discussed here (e.g. Dimov, 1992; Dimov, 1994; Burg et al., 1990, 1996a,b; Dimov et al., 2000) the boudins are considered equivalent to the stretching lineation, and parallel to the boudin axes is inferred the direction of tectonic transport. The author of this text measured the axes of boudins in the Vacha valley in the Central Rhodopes and found that they are really parallel to the axes of the folds. It is how it should be. However, there is a problem, because the direction of tectonic transport is not parallel to the axes of the boudins but at high angle to it. That is, if in the Central Rhodopes in the valley of the Vacha River, the fold axes are approximately north-south and the boudin axes are approximately north-south trending, then the tectonic transport can not be north-south as stated. In the same area, the tectonic transport directly observed from structures such as that shown on Fig. 2a is in fact close to west-east.

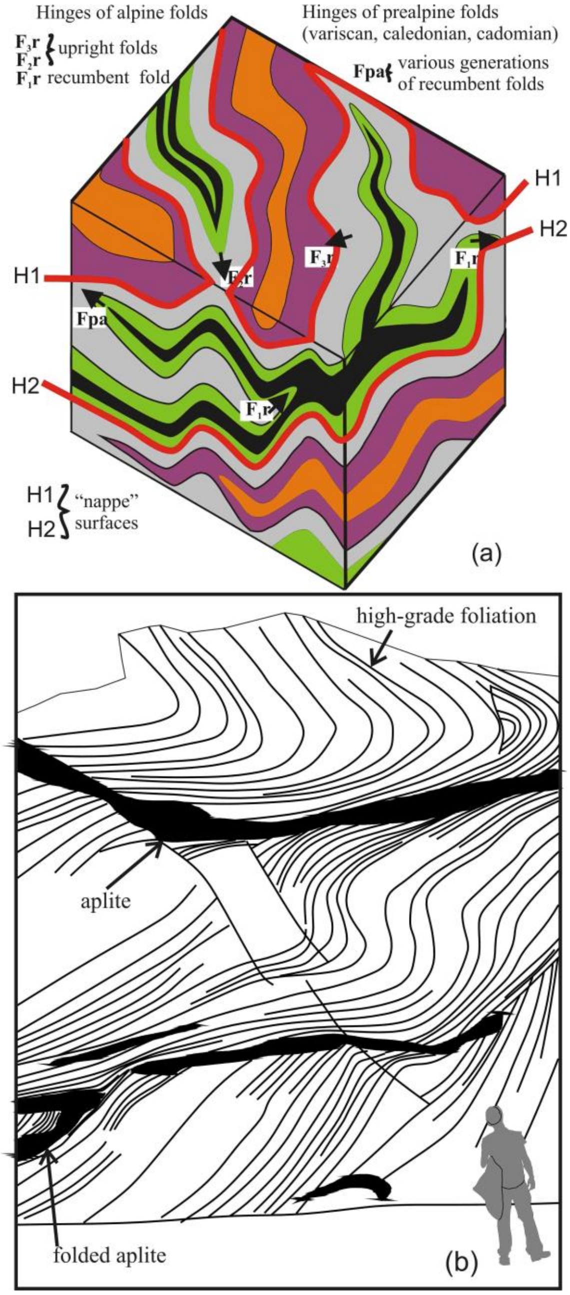

Fig. 2. (a) Conceptual block-diagram showing the geometrical relationships between various fold generations in the Rhodope massif. The block diagram was compiled from reinterpretation of unpublished geological map of the Central Rhodopes in scale 1:25000, assembled by D. Kozoukharov, stereographic projections and digital photographs of exposures. (b) Shallowly dipping shear surfaces injected by aplitic veins (black) that separate thrust sheets. The structure indicates dextral shear to east-northeast (80ENE). The axes of the recumbent folds (F_1r) are striking north, that is perpendicular to the observation surface. In the F_1r folds, high-grade metamorphic foliation is folded, which is locally cut by the aplites. Some of the aplitic veins are also shear–folded in the same dextral sense. The shear surfaces and the recumbent folds are folded in turn by gentle domes formed by the interference of the F_2r and F_3r. The outcrop is parallel to the axial plane of F_2r that is why the aplitic veins appear sub-horizontal in the section. Artificial outcrop in the locality Cankov kamak redrawn from a digital photograph

If it is from west to east the north-south oriented axes of boudins make complete sense. Otherwise, we are in gross inconsistency with the basics of structural geology, where the significance of the boudins is clearly exposed (for reference Wilson, 1985, Fig. 64).

Refolded early lineation

Refolding of early lineation is very common, and it can modify the lineation orientation making it unusable for kinematics analysis, unless very complex unfolding procedures are applied. It is shown on Fig. 3a how two different stretching lineations (Lh,Li) can be formed out of one primary lineation, that was folded around recumbent fold axes. Since recumbent folds are common in Rhodope and different generations of folds are present, refolding of lineations would be a rule, rather than exception. The orientation of the stretching lineation will depend on the reorientation pattern imposed by the folding. However, attempts to unfold lineation or evidence that fold geometry is accounted in the lineation studies in Rhodope are not present.

Pseudo-mineral (stretching) lineation

This lineation is formed by intersection of thin metamorphic layering such as gneissosity or shistosity and the outcrop surface (Fig. 3b). In essence, it is intersection lineation not stretching lineation. It can be sub-parallel to the axes of the transposed recumbent folds of the infrastructure, most of which are of unknown age, or it can be related to the open, upright, alpine folds of the suprastructure. In the second case, its orientation varies according to the geometry of the suprastructure folds. The observations of the author are that in localities, where existence of mineral stretching lineation is suggested (e.g. Dimov, 1994; Dimov et al., 2000) in fact intersection lineation is present. It might be, that intersection lineation is mistaken for stretching lineation. Of course, the intersection lineation can not be used for kinematics analysis in the way the stretching lineation is used. It is noteworthy, that the proponents of the nappe concept do not distinguish intersection lineation in Rhodope. The author of this text did not find reference for such lineation. Is it possible that it is completely absent in Rhodope?

Detachments relative to folds

The core complex model needs to accommodate two generations of upright folds. There is little or no comment so far on the role of the suprastructure's upright folding. When it happened? It must have happened during the extensional stage of the core complex formation. But how folding happens in extensional deformation? The general impression of the author is that some of the shear surfaces are in fact folded by the upright folds of the suprastructure. It is stated that the extension was of Oligocene-Miocene age (e.g. Bonev et al., 2006). However, paleonthological dating and stratigraphic correlations of the unmetamorphosed molasse sediments deposited on top of the high-grade rocks suggest, that at least part of the high-grade metamorphic sequence was at daylight surface as early as Maastrichtian-Paleocen (Goranov, Atanasov, 1991). That makes pretty slow exhumation. If the daylighting happened in the Maastrichtian, and upright cross-folding at shallow depths, which results in doming, happened prior to the Oligocene, then how important is the Oligocene extension?

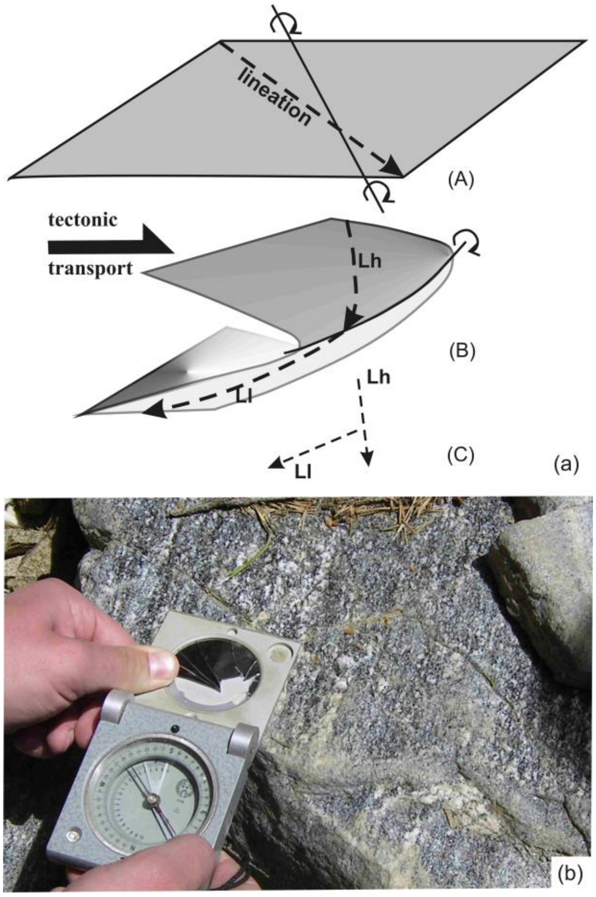

Fig. 3. (a) Sequence of sketches illustrating refolding of a lineation by a recumbent fold. Starting from a flat surface the lineation is folded around the hinge of a recumbent fold, so in the upper limb it acquires position (Lh), and in the inverted limb the position of the same lineation is (Li). Underneath are shown Lh and LI projected on a horizontal map plane, where they appear as two different orientations. If the recumbent fold is large and there is significant distance in vertical direction between the normal and inverted limb of the fold the two lineation directions may be interpreted as different lineations formed in different tectonostratigraphic units (e.g. Asenishka and Ardinska units). (b) Intersection lineation formed by intersection of thin gneissosity and the outcrop surface. The lineation is marked by elongated mineral sections but do not represent mineral growth parallel to the extensional direction of the strain ellipsoid

Conceptually wrong statements

Is stretching lineation parallel to the shear direction?

By definition the stretching lineation is not formed parallel to the shear direction but at 45° to the shear zone boundaries (e.g. Escher and Watterson, 1974; Means, 1987). If shear zone boundaries are sub-horizontal, looking in plan the lineation may be really parallel to the shear direction. If the shear zone boundaries are not horizontal or the rock domain is tilted by later folding the axes of the strain ellipsoids projected on a horizontal map plane would differ at any angle between 0° and 45° to the shear direction. So, even if true stretching lineation is striking north-south in the Central Rhodope, the tectonic transport may not be in the same direction.

What is direction of tectonic transport?

In many works about the Central Rhodope (e.g. Burg et al. 1990; Dimov, 1994; Burg et al. 1996a,b; Dimov et al., 2000 etch.) consistent north-south to northwest-southeast oriented mineral stretching lineation is mentioned, and "southwestward displacements of tens to hundreds of kilometres" (Burg et al. 1996a) is inferred parallel to the stretching lineation. The lineation is "formed by aligned micas and amphiboles, elongated quartz and feldspar grains and occurs in all rocks types parallel to the fold hinges" (Burge et al., 1996a,b). The direction of this lineation is assumed to be parallel to the principal axes of the strain ellipsoid.

Apart from the uncertainty, if the lineation described is really stretching lineation as stated, another problem arises, because in the world's experience the tectonic transport is not considered always parallel to the stretching lineation. Especially informative on the subject is the text of Cloos (1946) who wrote "Secondary flow ***perpendicular*** to the fold axes or ***in*** the direction of tectonic transport has been described by **54** authors (table 1, column 3). ***Stretching parallel*** to the fold axes or ***perpendicular*** to the direction of the tectonic transport was described by ***60*** authors. Secondary flow is known since the works of Sedgwick". It is apparent that Cloos makes clear distinction between the stretching direction and the direction of tectonic transport, and that the tectonic transport according to Cloos is perpendicular to the fold axes not parallel to them.

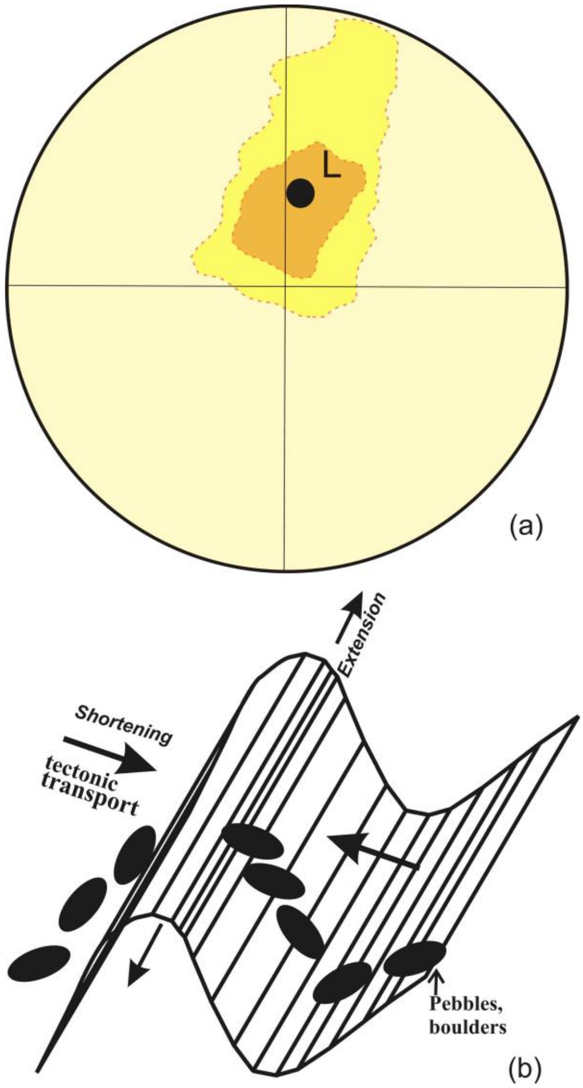

Fig. 4. Lineation marked by strongly deformed pebbles and cobles of the metamorphosed Chernogorovo Formation, which was folded by the Topolovgrad Syncline. (a) Statistical maximum of long axes of pebbles plunging to northeast is shown, found from 180 pebbles, cobles and boulders. (b) Sketch of the pebble orientation relative to the axes of the Topolovgrad syncline. The lineation is close to perpendicular to the axes of the syncline. This lineation is true stretching lineation and it is parallel to the tectonic transport but is perpendicular to the fold hinge

Direction of tectonic transport parallel to the fold hinges. Is it possible?

It is common to have lineation parallel to the fold axes. Many researchers, including the author of this text, studied deformed pebbles oriented parallel to the axes of the folds, even in completely unmetamorphosed sediments. But in no way this lineation is parallel to significant tectonic transport. The true large-scale displacement is perpendicular to the fold axes, unless all folds are sheath folds, but event the proponent of the nappe model (and the core complex model) stated that sheath fold are "occasionally observed" (Burg et al., 1996a).

The first attempt (Gerdjicov, 2004) to justify the existence of stretching lineation, which is parallel to the fold axes and parallel to the tectonic transport was made much after this relationships were first suggested and used in modeling (e.g. Burg et al., 1990; Dimov, 1992; Dimov, 1994; Burg 1996a,b). Gerdjicov (2004) attempted to show, that such relationships are indeed present and significant, but offered inconsistent reasoning. First, he needed to show that all folds discussed are sheath folds or folds formed in extreme sub-horizontal shear. Proving of such statement for the Rhodopes and SZ is impossible, even if some rare minor folds may approach this condition. Second, he apparently mistakenly took intersection lineation for stretching lineation. In the case of Sakar, which he discussed at length, he failed to spot real stretching lineation, which is in fact perpendicular to the fold axes (Fig. 4). Finally, his reasoning was developed for a geological setting, in which he believed the deformation sequence was very simple, the metamorphism was only alpine in age and the granitic plutons in southeast Bulgaria are Cretaceous or at most Late Jurassic in age. In his later works (since 2005) he radically changed his ideas and admitted that the granites are variscan, the metamorphism older and the deformation more complex.

Conclusion

The supra-infrastructure concept requires clarification of the geometrical relationships between the fold generations. It can be done only if overprinting relationships are examined in details. For this reason this concept can help in the understanding of the local geology better than other models. If the criticism on the use of stretching lineation exposed in this paper is correct, then the structural geological basis for the separation of the Ardinska and Asenishka units in the Rhodope Massif are not correct.

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