Himalayan Geology, Vol. 22 (1), 2001, pp. 191-198, Printed in India

Along-Strike Shearing instead of Orthogonal Compression : A different viewpoint on Orogeny and Regional Metamorphism

C. STRUTINSKI[1] AND A. PUSTE[2]
[1]*Geological Institute of Romania, Cluj Branch; POB 181; RO-3400 Cluj 1 / Romania*
[2]*Babes-Bolyai University, 1, Kogalniceanu Str., RO-3400, Cluj, Romania*

Abstract: Orogeny has been regarded for over a century as a compressional phenomenon due either to contraction or to lithospheric collision. However, generation of *linear* structures like orogens can hardly be explained by variation over large *areas* of stress gradients, as is to be expected in the rigid-plate convergence assumption. Lateral escape - implied by newer plate-tectonics interpretations to overcome this difficulty - might apply to some degree, but should by no means be more important than up and outward escape, i.e., in the direction of minimum principal stress. Movement indicators in regional metamorphic rocks have shown that tectonic transport along the orogens is a matter beyond question but also that this transport begins at a very early stage, a situation that contradicts the lateral escape model. Therefore it is assumed in this paper that the lateral movement is not due to compression, but to transcurrency, which has both the maximum and minimum principal stresses in the horizontal plane. This agrees particularly well with the observed belt-like distribution of deformation. Two models are advanced, the *corridor* and the *gliding-blocks* model, which are not mutually exclusive, even if each of them relates to a specific geotectonic setting.

INTRODUCTION

Traditionally, fixistic hypotheses try to explain global tectonics assuming that the Earth crust or the lithosphere as a whole is welded to the underlying mantle, being not able to independently move over it, i.e. to decouple sub-horizontally from it. At the other extreme, mobilistic hypotheses claim that the lithosphere either drifts freely on the mantle (continental drift hypothesis), or that it is transported passively by mantle currents, imagined to build up a system of convection cells located in the so-called asthenosphere and the underlying mesosphere. Thus, plate tectonics attributes orogeny to a compressional process, occurring where lithospheric plates collide above descending branches of such assumed convection cells. Today this view has become almost axiomatic in geological science, in total disregard of 'hard-core' data. Here we discuss some of the evidence that negate plate tectonics explanation, and argue in favour of an alternative model.

ELEMENTS AT ODDS WITH PLATE TECTONICS

It is beyond the scope of this paper to give a thorough analysis of the shortcomings of plate tectonics in regard of orogeny. Instead, some critical topics are addressed where geophysical, geochronological and/or geochemical data provide evidence against the collision model of orogeny.

- Though plate-tectonics theory assumes the existence of a complex system of convection cells in the upper mantle, and, accordingly, of conveyor belts carrying lithospheric plates against each other in order to generate orogens, there is so far no indication in favour of this process. Sub-horizontal flow at asthenospheric levels in the predicted direction of plate motions should easily be revealed by regionally consistent seismic anisotropy patterns within the asthenosphere. However, the results obtained to this day show rather systematic variations of the seismic anisotropy over relatively short distances, a feature that dismisses the conveyor-belt hypothesis (see, for instance Silver, 1996).

- Moreover, there is no reason either for assuming the existence of a continuous asthenospheric layer at the base of the lithosphere. Analysis and subsequent inversion of regionalized Rayleigh wave dispersion relations under the Baltic and Canadian shields allowed Calcagnile *et al.* (1997) to conclude that the upper mantle in the north-central part of both these areas has no low velocity zone or in the extreme case this is virtually absent down to a depth of 200-250 km. This observation points to a lithosphere/mantle welding in the fixists' sense, at least under the old shields, running counter to plate tectonics expectations.

- The collision of plates, as advocated by plate tectonics, should conceivably destroy pre-existent configuration at convergent plate margins and assume the occurrence of more or less upright structures, in accordance with the fact that in horizontal compression the least principal stress is always near-vertical. Such steep structures are observable, indeed, at the surface, but as a rule they do not continue to depth, as is witnessed by the seismic reflection profiles in most orogenic regions of the world. These show, on the contrary, a fairly well-expressed horizontal layering of the lithosphere, only locally disturbed by structures attributable to compression (the reflection profiles from the Alps published by Frei *et al.*, 1989, should be interpreted in the latter sense).

- The well-known assumption of plate tectonics, that, along a Benioff zone, cold (i.e. high-velocity)oceanic crust is subducted is likewise called into question by latest tomographic studies. Thus, under the Hellenic trench, instead of the expected high-velocity zone, a low-velocity zone has been found to mark the "subduction" plane (Drakatos *et al.*, 1996). According to Drakatos and co-workers this is a highly "surprising feature", showing "a possible connection with Alpidic orogenesis".What they do not say in straightforward terms is that their finding is at variance with subduction fundamentals, as is the fact, mentioned by Dewey and Shackleton (1984), that all giant ophiolite nappes have been tectonically emplaced shortly after their generation, in a still hot state.

- According to the plate-tectonics theory orogeny should be a cooling event, as, due to lithospheric thickening, orogenic geotherms are advected downward, leading to a cold and seismically fast upper mantle. As revealed by various seismic studies, quite the opposite is true, inducing some authors to speak about an "orogeny paradox" (Silver and Chan, 1991; Silver, 1996). Together with the obviously coherent crust-mantle deformation of orogenic zones, this aspect underlines the weakness of basic tenets of the convergence model of orogeny.

- Within orogenic belts the early beginning of metamorphism, prior to any assumed collision, is another unexplained fact of the plate-tectonics theory, producing much confusion among its supporters. In this respect, the "vexing question" (Dewey, 1982) of early Caledonian (Grampian/Finnmarkian), as well as of Eo-Variscan (Ligerian) and Eo-Alpine metamorphism should be mentioned.

- The widespread occurrence of so-called flat metamorphic belts in orogenic structures, e.g., in the Caledonides (Hanmer, 1981; Hutton, 1982; Piasecki, 1988), Variscides (Audren, 1990), and Alpides (Ratschbacher, 1986), and the ubiquitous orogen-parallel extension lineations within these belts (Ellis and Watkinson, 1987) is another feature that cannot successfully be integrated into models derived by tangential compression. This is because, according to the majority of authors, "the orientation of regionally constant extension lineations ... directly relates to shear-zone movement direction" (Daly, discussion in Woodcock, 1986), that should be orthogonal, not parallel, to the orogen in a converging plate framework.

- There appears to exist, however, a sub-horizontal orthogonally-directed flow in regional metamorphic belts, but this is the fluid flow, imagined by Ferry (1992) to be part of a giant hydrothermal system. In accordance with the model for coupled fluid-flow and mixed-volatile mineral reactions (Baumgartner and Ferry, 1991), Ferry concluded that metamorphic fluids flow laterally from regions of low to regions of high temperature, i.e. from peripheral towards axial zones of orogens. Assuming the converging-plates model, this would mean flow in the direction of the maximum principal stress, an unacceptable situation.

- Lastly, another aberrant assumption of plate tectonics should be mentioned, which we may refer to as the HP(high-pressure)-belts paradox. According to plate tectonics the rocks of these belts underwent a long tectonic transport (first to great depths and then back to the surface) along what is considered as the most mobile and deformable part of the orogen, i.e. the subduction zone. Yet, compared with rocks of MP (medium-pressure)-belts, they are usually less deformed, frequently preserving their pre-metamorphic structures (Newton and Fyfe, 1976; Ernst, 1993; Ernst and Liou, 1995). Thus, for the Franciscan complex, Ernst and Liou (1995) state that "although metashaly sections have been converted to chaotic melange, many metasandstone-rich units retain a measure of stratal coherence, and apparently ascended from subduction depths more or less intact".

THE NEW APPROACH : SHEAR-BELT TECTONICS

To overcome inconsistencies, the plate tectonics theory is confronted with today, we have imagined a new geotectonic hypothesis, starting from a distinctly different approach of regional metamorphism.

One of the basic assumptions in this approach is that the structural elements (schistosity, extension lineation) of metamorphic rocks truly indicate the direction of tectonic transport, and, as this is mainly parallel to orogenic belts, it follows that the principal deformation associated with them must be related to transcurrent-type movement, not to convergence. Flow under the lithosphere, indicated by

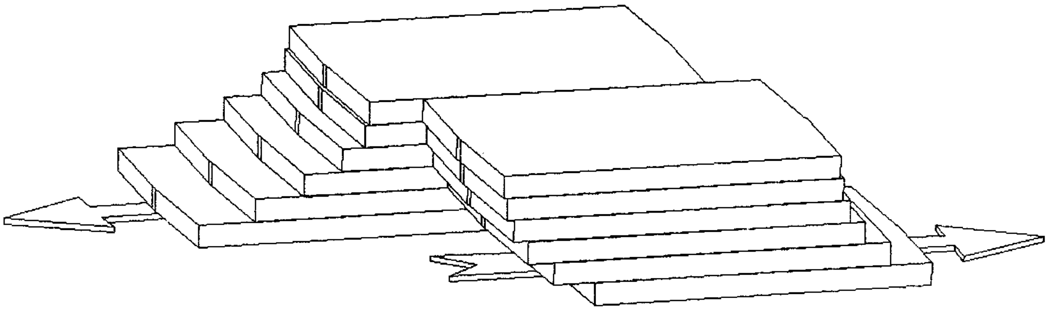

Fig. 1. Shearing of the lithosphere above opposed asthenocurrents, visualized by two adjoining decks of tiles (Strutinski, 1994).

seismic investigations, is likewise subparallel to the trend of orogens and evidences maximum rates just below these (e.g. Ramananantoandro, 1988; Silver, 1996), emphasizing coherent crust-mantle deformation and temperature-induced weakening of both. This means that at sub-lithospheric depths we probably have to deal with *asthenocurrents*, rather than with an undifferentiated asthenosphere, as invocated by the plate-teconics assumption.

The heat necessary to raise the temperature along a transcurrent system is considered to be produced by the system itself due to shear-heating in both crust and uppermost mantle. This idea has repeatedly been emphasized by us (Strutinski, 1990; 1994; 1997) and seems to correlate well with the conclusions of Silver (1996), who stresses that deformation is likely to be the main heat supplier during transpression-linked orogenesis. Related ideas about "strain-heating" during orogeny were advanced earlier by Reitan (1988), whose calculations of heat production led him to the conclusion that strain-generated heat is a "significant component of the set of contributors to the temperatures found in orogenic/metamorphic belts".

To explain the generation of flat metamorphic belts and of the sub-horizontal lithospheric layering as revealed by seismic reflection profiles, we are depending on shearing experiments (Tchalenko, 1970), which showed that in strike-slip arrangements the initial deformation ("pre-peak strength deformation") is characterized by a sub-horizontal homogeneous straining in the region of the future sub-vertical shear zone. In consequence of such straining, the matter subject to deformation is stretched longitudinally, marker circles being turned into ellipses. At lithospheric level, we suppose that, due to differential frictional coupling between sub-horizontal material planes, a more or less homogeneous deformation is produced, that may be visualized, at a gross approximation, by two adjoining decks of tiles progressively "sheared" along their length into opposite directions (Fig. 1). This framework is based on the principle of laminar flow that assumes translation of material planes along parallel stream lines (Fig. 2a). However, as it is likely that flow in the lithosphere results from progressive simple shear, thus being non-coaxial (Lister and Snoke, 1984), the image is rather different (Fig. 2b), suggesting sub-horizontal "flattening". This characteristic "flattening" of regional metamorphic rocks has usually been considered as being due to orogenic compression, though some prominent authors of the first half of the century doubted it. In a remarkable paper on the development of schistosity in metamorphic rocks, DeLury (1941) stressed on the fact that "in tectonic discussion most attention is paid to schistosity of the axial-plane type, while relatively little is devoted to

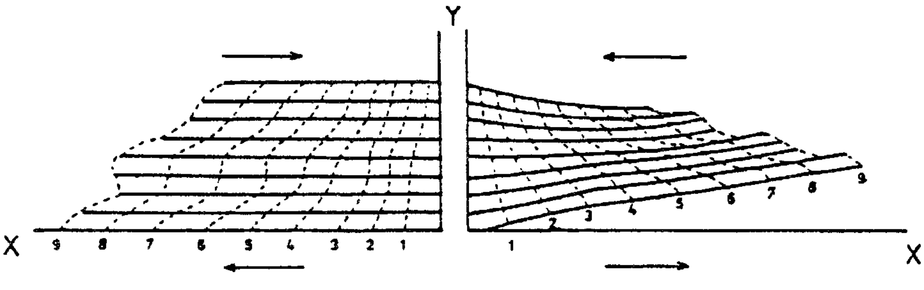

Fig. 2. Laminar translational (a), and laminar non-coaxial flow (b), illustrated by the projection of an initially vertical plane at 9 successive stages. The models assume discontinuously growing velocity from top to bottom. Continuous lines represent shear planes. Sketch (b) modified after Lister and Snoke, 1984.

bedding-plane foliation, which may be of greater significance for testing purposes". In his opinion, bedding-plane foliation (i.e., sub-horizontal foliation) must be regarded as being "closer to the causes of movement", which he considers to be horizontally migrating magma masses. These are exerting a *differential frictional drag* on the overlying rock "carapace", which is stretched and subject to a "more or less bodily horizontal displacement". By this mechanism, metamorphic schistosity is thought to be generated, a feature that pre-dates folding, thus initiation of compressional orogenic events.

At about the same time, in France, Roques (1941) made also a clear distinction between the slaty cleavage attributable to compression and the metamorphic schistosity ("schistosité cristallophyllienne") that is "always in perfect concordance with bedding", being imprinted on rocks before folding, as they still lay in a horizontal position. But a horizontal schistosity requires either a vertical pressure or a horizontal stretching. Vertical pressure can only be due to load and its increase with depth can correspond only to an increase of hydrostatic pressure, that is, as known, unable to produce anisotropic fabrics. From here, the conclusion of Roques, that horizontal stretching should be regarded as the ultimate cause of schistosity. This inference seemingly impressed Read (1948), who wondered "whether the orthodox compressional view of metamorphism is really valid", glancing at the shortly before launched concept of *convection currents* in his attempt at identifying the "prime agent in the production of schistosity". Without reaching a conclusion, he felt "more comfortable in viewing horizontal schistosity, especially on bedding, as the result of frictional drag or extension rather than orogenic compression".

The reality of bedding-plane schistosity, at least recognized as an unsolved problem until the fifties of our ending century, was then almost forgotten in the sixties, as the interest of the geological community shifted suddenly from the continents to the oceanic domains. It took some decades until the problem was raised again by Hanmer (1981), in recognizing the existence of a "flat" and a "steep" belt in the central part of the Newfoundland Caledonides. According to his interpretation of the field data, interaction between an active shear zone and the rising diapirs resulted in the formation of a belt of sub-horizontal foliation and a belt where foliations are upright to vertical. Hanmer stressed that in both belts the shear direction was *along* the strike of the orogen. Particularly one of his two possible structural interpretations is suggestive of the relationship between these two belts within the orogen (Fig. 3) and represented one of the starting points of our theoretical considerations. We have diversified his views by imaging two different shear-belt-derived models that are not mutually exclusive but may combine to some degree, even if each of them relates to a specific geotectonic setting. They are termed as the *corridor* and the *gliding-blocks model*, respectively (Fig. 4).

The *corridor model* (Fig. 4a) finds its applicability particularly in orogens generated in a (sub-) equatorial position, like the Caledonian, Variscan and Alpine belts of North America, North Africa and Eurasia. As the most plausible driving force we assume (sub-) equatorial eastward-flowing mantle currents (=asthenocurrents) created due to zonal rotation (Jardetzky, 1954; Gilliland, 1964, 1973).

In the first stage of pre-orogenic metamorphism, the differential coupling and resulting drag along sub-horizontal planes creates above the asthenocurrent a *flat metamorphic belt*, showing a well-defined vertical zonation, due to P-T variation and to deformation types (brittle, brittle-ductile and ductile) successively operating in the lithosphere and uppermost mantle. Accordingly, a variety of structures are being created while metamorphic fluid is directed across temperature and pressure gradients towards the future sub-vertical zones of failure. These occur in the second (orogenic) stage because shear stress cannot be accommodated any further by primary homogeneous straining. In this way deformation is steadily concentrated along the "walls" of the corridor, giving birth to high-strain *steep metamorphic belts*, while the former flat belts cease to evolve, preserving their characteristics (quasi-horizontal layering sub-parallel to bedding and comparatively low strains).

The metamorphism operating in the corridor model is mainly of barrovian type (medium P/T rate: Miyashiro, 1994), having the necessary energy supplied by shear heating.

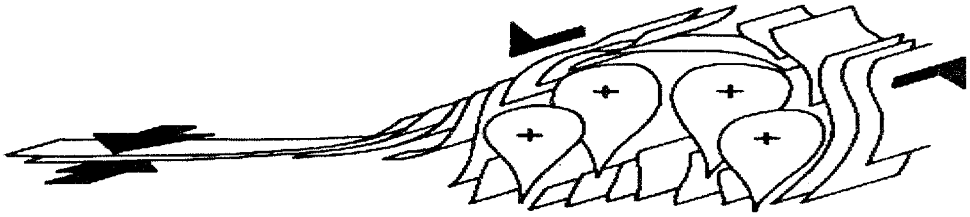

Fig. 3. Schematic representation of a possible structural relationship between flat and steep belts (modified after Hanmer, 1981).

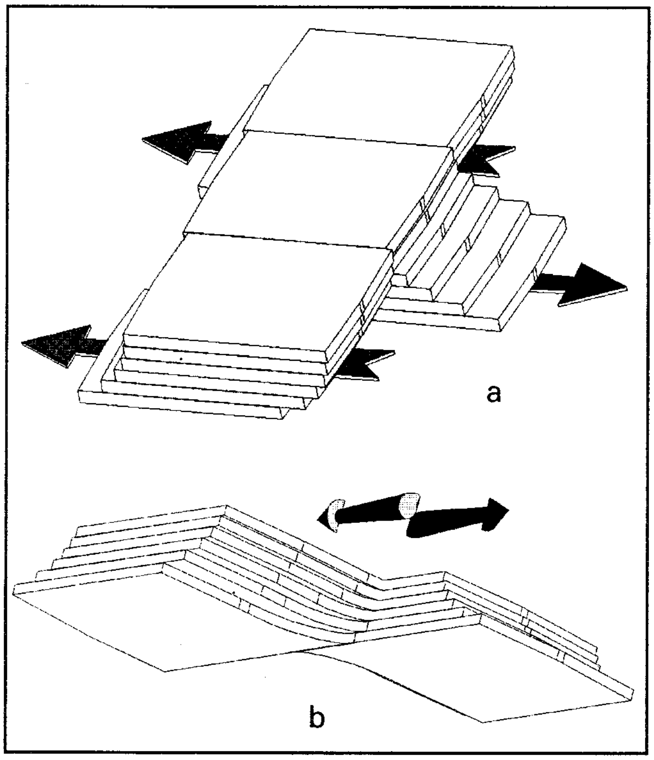

Fig. 4 Shearing along a pair of dextral-sinistral sub-vertical planes: the corridor model (a); simple block-shearing: the gliding-blocks model (b).

Progressive metamorphic zones are ruled by growing $\Delta T/\Delta P$ rates (T rises faster than P). As is easily seen, the characteristic trait of the model is the existence, along the margins of such a (sub)-equatorially oriented corridor, of at least two steep belts (i.e. sub-vertical shear zones), a northern sinistral, and a southern dextral one. Both belts may be framed outwards by regions having a common geologic history (e.g. pre-Caledonian evolution of Baltica and Laurentia), but delimiting to the interior pieces of crust seemingly "exotic" as compared to their borderlands (e.g. Avalonia and Cadomia in Caledonian and Variscan times, respectively, see Figure 5). This arrangement may well be explained by the assumption of differential eastward drag, due to zonal motion, but remains a matter of dispute in the plate-tectonics framework.

The *gliding-blocks model* (Fig. 4b) may better explain the metamorphism occurring along the circum-Pacific orogens (Strutinski, 1994), as well as along local shear belts. Here a stress field leading to sub-vertical shearing of rigid lithospheric blocks is required to drive orogeny and metamorphism. Particularly in the case of circum-Pacific orogens it appears that shortly before shear-failure, the crust was capable to sustain large deviatoric stresses of the order of some kilobars (tectonic overpressure). For a normal sialic crust the occurrence of such high stresses is confined to the upper 20 kilometers (Brace and Kohlstedt, 1980). It is this environment, characterized by great unrelaxed stresses, inhibition of motion and its corollaries - fluid circulation and shear heating, that represents the locus of high-pressure (HP) metamorphism (metamorphism of high P/T rate: Miyashiro, 1994). Burial or "subduction" to great depths, as inferred by plate tectonics, are not needed, and are contradicted by mode of occurrence and structural features of the rocks. Progressive metamorphic zones are ruled by decreasing $\Delta T/\Delta P$ rates (P rises faster than T). Instead of HP metamorphism, we would prefer the term dynamo-static (or franciscan) metamorphism, as opposed to dynamo-thermal (barrovian) metamorphism. This dynamo-static metamorphism of circum-Pacific orogens may be considered as a pre-orogenic equivalent of the dynamo-thermal metamorphism that generates the flat belts of equatorial orogens. Other than in the corridor model, where the transition from the pre-orogenic to the orogenic stage is more or less gradual, in the gliding-blocks model the pre-orogenic stage is followed by a period of fast stress relaxation, as a consequence of lithospheric bursting along the forthcoming shear belt. It is assumed that during this sub-stage the dynamo-static belt is *partly* destroyed, the former HP structures and assemblages being replaced by others, typical for rocks of the blueschist-facies (schistose fabric and parageneses dominated by so-called stress minerals, e.g. glaucophane, chloritoid, kyanite, epidote-clinozoizite a.o.). Field relations show that through this special type of metamorphism the transition from the dynamo-static to the dynamo-thermal orogenic metamorphism is realized, the reason why we called it transfer metamorphism. Under certain circumstances, however, both dynamo-static and transfer

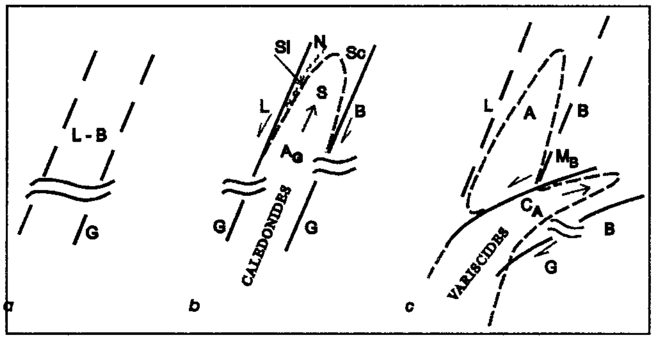

Fig. 5. Orogenic creep along corridors with subsequent insinuation of "exotic" terranes, exemplified in the zone of interference between Baltica and Laurentia. (a) - precursory Caledonian stage; (b) - final Caledonian stage; (c) - Variscan stage.

B - Baltica A_G - Avalonia (piece of Gondwana)
G - Gondwana C_A - Cadomia (piece of Avalonia)
L - Laurentia M_B - Midland craton (piece of Baltica)
SI - Iapetus Suture
Caledonides from: - Scandinavia (S_C)
- North Brittany (N)
- South Brittany (S)

metamorphisms are only faintly developed or missing (e.g., in the Peruvian Andes). This may be an indication that the lithosphere was unable to sustain very large stresses, yielding relatively early and allowing only dynamo-thermal metamorphic belts to develop. Conversely, stress concentrators may locally induce dynamo-static metamorphism also in equatorial shear belts that principally conform to the corridor model.

Orogens that evolve according to the gliding-blocks model are most typical in displaying also low-pressure metamorphic belts (low P/T belts: Miyashiro, 1994), or belts of stato-thermal metamorphism* The term emphasizes that, like the dynamo-static metamorphism, the stato-thermal metamorphism develops under more or less static conditions, as inferred from rock fabrics. However, tectonic overpressures are apparently absent, while a high temperature gradient exists, that is demonstrably due to thermal doming and/or granitic intrusion. It is tempting to consider that paired metamorphic belts, like the Sanbagawa-Ryoke belt of Japan, develop only where transcurrent shearing is markedly oblique. Under such circumstances heat generated in the process is conducted upwards into the hanging wall, the footwall remaining relatively cold and preserving the HP/LT character of the pre-orogenic stage. This would imply that in the hanging wall telescoping of a previous HP/LT belt by a HT/LP belt must have occurred. That such telescoping process with complete obliteration of HP mineral assemblages is possible, is demonstrated by some Alpine examples (Ernst, 1971).

Consistent with the shear-belt hypothesis is the fact that both temperature and pressure increase horizontally towards the axial zone of a steep belt** , together with the rate of deformation. In other words, we are dealing with relatively steep horizontal gradients. From here it is fully understandable that only some tens of kilometres beyond the axis, rocks are but "feebly metamorphosed" and "flat-lying" (Ernst, 1971). Such a situation is hard to explain in the plate-tectonics concept, that assumes constant pressures over large distances due to tentatively assumed ridge-push or slab-pull driving mechanisms.

Even if formally there is no serious reason to dismiss Miyashiro's (1994) classification of regional metamorphic rocks, we think that it starts from false premises, such as the compression assumption and the disregard of environment and structure of metamorphic rocks. Therefore it fails to give a real picture of the metamorphic phenomenon during orogeny. It was our task to present an alternative to his model and to show that metamorphism may be fully understood only if beside the static factors (P,T,X), the dynamic ones (friction coupling and derived stimulation or inhibition of motion and deformation) are also taken into consideration. Synthetically, the resulting types of metamorphism are presented in Figure 6.

CONCLUSIONS

The two models of regional metamorphism, that have been shortly outlined above, give a fairly well explanation to a series of facts that are unsatisfactorily integrated in

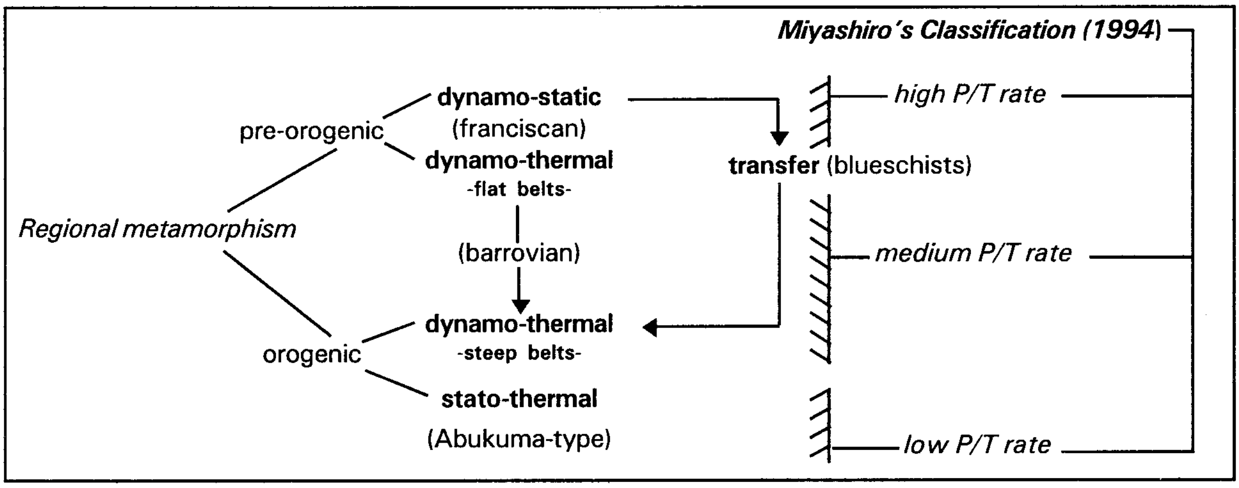

Fig. 6. The types of regional metamorphism according to the shear-belt model of orogeny. The evolution trend (for details see text) and correspondence to Miyashiro's classification (1994) are shown.

* The attributes dynamo-thermal, dynamo-static and stato-thermal as referred to metamorphism were introduced into the geologic literature by Daly (1917). It should be noted that we have taken over this terminology without its initial meaning.

** However, in the orogenic stage the pressure in the axial zone actually drops to a constant (residual) value.

compression-derived models of plate tectonics. The most important are:

- the existence of two types of metamorphic belts (flat and steep belts, respectively) and the peculiar spatial and temporal relationship between them;
- the relatively early beginning of the metamorphic process, prior to any implied collision;
- the sub-horizontal extension lineation within metamorphic belts, that is prevailingly parallel, not perpendicular, to the trend of orogens;
- the seismic anisotropy of the upper mantle, indicating coherent crust-mantle deformation during orogeny and its fossilization through time, a fact that contradicts the conveyor-belt assumption of plate tectonics.

Acknowledgements : We wish to express our thanks to J.Mac Dickins and Dong Choi for facilitating the publication of this paper and for their restless work in promoting heretic ideas among the geological community worldwide. Thanks are also due to an unknown reviewer, for his critical comments that helped to improve the manuscript.

References

AUDREN, C., 1990. Evolution tectonique et métamorphique de la chaîne varisque en Bretagne méridionale. *Schweiz. Min. Petr. Mitt.*, **70**, 17-34.

BAUMGARTNER, L.P. AND FERRY, J.M., 1991. A model for coupled fluid-flow and mixed-volatile mineral reactions with applications to regional metamorphism. *Contrib. Mineral. Petr.*, **106**, 273-285.

BRACE, W.F. AND KOHLSTEDT, D.L., 1980. Limits on lithospheric stress imposed by laboratory experiments. *Jour. Geophys. Res.*, **B11**, 6248-6252.

CALCAGNILE, G., DEL GAUDIO, V. AND PIERRI, P., 1997. Lithosphere-asthenosphere system in shield areas of North America and Europe. *Annali di Geofisica*, **XL**, 1043-1056.

DALY, R.A., 1917. Metamorphism and its phases. *Geol. Soc. America Bull.*, **28**, 375-418.

DE LURY, J.S., 1941. Correlation of schistosty and tectonic theory. *American Jour. Sci.*, **239**, 57-73.

DEWEY, J.F., 1982. Plate tectonics and the evolution of the British isles. *Jour. Geol. Soc. London*, **139**, 371-412.

DEWEY, J.F. AND SHACKLETON, R.M., 1984. A model for the evolution of the Grampian tract in the early Caledonides and Appalachians. *Nature*, **312**, 115-121.

DRAKATOS, G., KARANTONIS, G. AND STAVRAKAKIS, G., 1997. P-wave crustal tomography of Greece with use of an accurate two-point ray tracer. *Annali di Geofisica*, **XL**, 25-36.

ELLIS, M. AND WATKINSON, A.J., 1987. Orogen-parallel extension and oblique tectonics: the relation between stretching lineations and relative plate motions. *Geology*, **15**, 1022-1026.

ERNST, W.G., 1971. Metamorphic zonations on presumably subducted lithospheric plates from Japan, California and the Alps. *Contrib. Mineral. Petr.*, **34**, 43-59.

FERRY, J.M., 1992. Regional metamorphism of the Waits River Formation, Eastern Vermont: delineation of a new type of giant metamorphic hydrothermal system. *Jour. Petr.*, **33**, 45-94.

FREI, W., HEITZMANN, P., LEHNER, P., MULLER, S., OLIVIER, R., PFIFFNER, A., STECK, A. AND VALASEK, P., 1989. Geotraverses across the Swiss Alps. *Nature*, **340**, 544-547.

GILLILAND, W.N., 1964. Extension of the theory of zonal rotation to explain global fracturing. *Nature*, **202**, 1276-1278.

GILLILAND, W.N., 1973. Zonal rotation and global tectonics. *American Assoc. Petroleum Geologists Bull.*, **57**, 210-214.

HANMER, S., 1981. Tectonic significance of the north-eastern Gander Zone, Newfoundland: an Acadian ductile shear zone. *Can. Jour. Earth Sci.*, **18**, 120-135.

HUTTON, D.H.W., 1982. A tectonic model for the emplacement of the Main Donegal Granite, NW Ireland. *Jour. Geol. Soc. London*, **139**, 615-631.

JARDETZKY, W.S., 1954. The principal characteristics of the formation of the Earth's crust. *Science*, **119**, 361-365.

LISTER, G.S. AND SNOKE, A.W., 1984. S-C Mylonites. *Jour. Struct. Geol.*, **6**, 617-638.

MIYASHIRO, A., 1994. *Metamorphic petrology.* UCL (University College London) Press, London, 404pp.

PIASECKI, M.A.J., 1988. Strain-induced mineral growth in ductile shear zones and a preliminary study of ductile shearing in western Newfoundland. *Canadian Jour. Earth Sci.*, **25**, 2118-2129.

RAMANANANTOANDRO, R., 1988. Seismic evidence for mantle flow beneath the Massif Central rift zone (France). *Canadian Jour. Earth Sci.*, **25**, 2139-2142.

RATSCHBACHER, L., 1986. Kinematics of the Austro-Alpine cover nappes: changing translation path due to transpression. *Tectonophys.*, **125**, 335-356.

READ, H.H., 1948. A commentary on place in plutonism. *Quart. Jour. Geol. Soc. London*, **CIV**, 155-205.

REITAN, P.H., 1988. Global dynamics and the temperatures of metamorphism. *Bull. Geol. Inst. Univ. Uppsala*, N.S., **14**, 21-24.

ROQUES, M., 1941. Les schistes cristallins de la partie sud-ouest du Massif Central français. *Mém. Serv. Carte Géol. France*, 512pp.

SILVER, P.G., 1996. Seismic anisotropy beneath the continents: Probing the depths of Geology. *Annu. Rev. Earth Planet. Sci.*, **24**, 385-432.

SILVER, P.G. AND CHAN, W.W., 1991. Shear wave splitting and subcontinetal mantle deformation. *Jour. Geophys. Res.*, **96**, 429-454.

STRUTINSKI, C., 1990. The importance of transcurrence phenomena in mountain building. *In:* BELOUSOV, V. *et al.* (eds.), *Critical aspects of the plate tectonics theory,* Theophrastus Publ. S.A., Athens, **II**, 141-166.

STRUTINSKI, C., 1994. An orogenic model consistent with Earth expansion. *In:* BARONE, M., SELLERI, F. (eds.), *Frontiers of Fundamental Physics,* Plenum Press, New York, 287-294.

STRUTINSKI, C., 1997. *Causal relations between transcurrent systems and regional metamorphism, with reference to the Upper Proterozoic - ? Cambrian formations of Central Dobrogea* (Ph.D. Thesis, in Romanian).

TCHALENKO, J.S., 1970. Similarities between shear zones of different magnitudes. *Geol. Soc. America Bull.*, **81**, 1626-1640.

WOODCOCK, N.H., 1986. The role of strike-slip fault systems at plate boundaries. *Royal Soc. London Philos. Trans., ser. A,* **317**, 13-29.