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GEOLOGY

The General Crustal Folding of Mobile Belts

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It is known that the Earth's crust is subjected to thickening and lithostructural transformations during collision. Terms such as "syncollision metamorphism (magmatism)" are widely used in the recent geological literature. However, what mechanism is responsible for crust thickening during collision-related compression and where is the energy stimulating lithostructural transformations of the crust localized? These are pressing and intensely debatable issues of recent geology. Previously, we demonstrated [1, 2] that they can be solved based on undulatory crustal deformations related to oriented horizontal compression recognized as general crustal folding (GCF) [3].

Since the works by E. Argand, who defined "basement folds," many researchers considered the problem of crustal folded deformations. However, the mechanism of folding and related geological processes of crustal transformation remained insufficiently studied from the standpoint of theoretical and experimental aspects. According to some researchers [4, 5], crustal folds differ from gentle isoclinal folds in the sedimentary cover only in their size. The present paper discusses a modified version of our theoretical model of longitudinal crustal warping proposed. The model is based on recent concepts of the rheologically layered crust and assumption of horizontal slipping of its layers relative to each other [6 and others].

Loss of flexural stability under horizontal compression. According to the model of the rheologically layered crust, the crust can be conditionally subdivided into the upper (elastic) and lower (plastic) parts. The upper crust is considered as the *competent* layer sandwiched between two *incompetent* layers: the ultraplastic atmosphere (hydrosphere) and lower crust (Fig. 1a). The temperature and lithostatic pressure increase downward. Deformations occur in the scale of geological time. Based on mathematic calculations, Turcotte and Shubert [7] demonstrated that the loss of crustal flexural stability during horizontal compression needs huge stresses and assumed that such a process is impossible. However, they believed that the formation of thrusts of respective scales is rather possible. As is shown in [8], the thrust and longitudinal bend represent a *tectonic pair.* Consequently, the formation of thrusts in the upper crust should result in the loss of its flexural stability (Fig. 1a). This is only one of the possible scenarios. Stress is a variable vector and any large heterogeneity in the upper crust should provoke redistribution of the stress field and loss of its crustal flexural stability (Fig. 2). The loss of flexural stability in some area should instantly trigger initiation of folding over the entire field of tectonic stresses.

Main elements of the GCF. Tensile settings developed in the case of a positive longitudinal bend (Fig. 1b) above the neutral surface (NS) may result in the formation of the axial graben and sedimentation therein. The existence of the compression setting and transformation of mechanical energy into thermal and other types of energy leads to rapid heating of large rock volumes beneath the NS. The flexural stress shows a direct correlation with the distance to the NS. Maximal energy consumption occurs near the base of the upper crust. Thickening of the crust in the compression zone and squeezing out of heated plastic material to the basal part of the graben stimulates the formation of the transverse bend in the course of the longitudinal one. The *K* boundary is insignificantly displaced (mostly, downward). Thickening of the lower crust due to horizontal compression leads to intensification of transverse warping of the upper crust. An additional vertical load on the lower crust is provided by indentation of the upper crustal block along boundary thrusts. The *M* boundary sags downward.

In case of a *negative bend*, the compression zone is located above the NS within cold and brittle rocks subjected to an insignificant lithostatic loading. A tectonic wedge (horst) or a system of such structures is formed to provide warping under such conditions. This process is accompanied by large-scale brecciation of rocks in upper layers, plicative deformations of sedimentary sequences, and formation of gentle overthrust-type shears in marginal parts of the structure. Near the NS, horizontal compression with increasing lithostatic load fosters insignificant heating and foliation of rocks. Below the NS, horizontal extension and vertical com-

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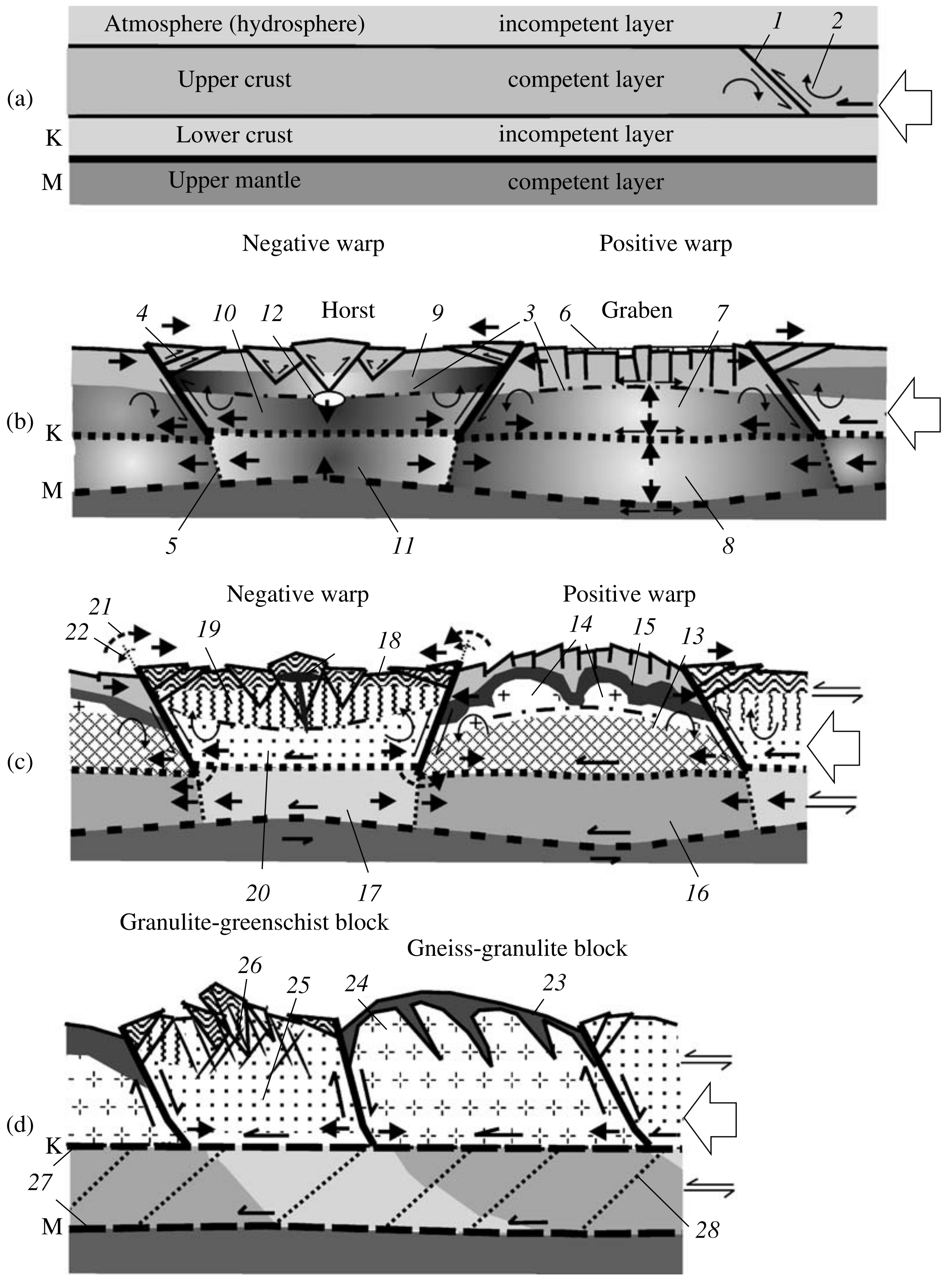

Fig. 1. Dynamics of the GCF. (a) Rheologically layered crust and loss of its flexural stability; (b) main elements of GCF; (c) lithostructural transformations of the crust during its warping; (d) transformation of the GCF into imbricate thrust structures. (*1*) Thrust; (*2*) bending moments; (*3*) neutral surface; (*4*) shear fissures (wedge dislocations), near-thrust swells; (*5*) plastic displacement zone; (*6*) synfolding sedimentary rocks; (*7, 8*) compression zones in the upper and lower crust, respectively; (*9*) compression zone; (*10, 11*) extension zones in the upper and lower crust, respectively; (*12*) magma chamber; (*13*) heating and high-pressure metamorphism area; (*14*) dome-shaped structures; (*15*) high-grade zoned metamorphism; (*16*) heating and high-pressure metamorphism area in the lower crust; (*17*) heating and low-pressure metamorphism area; (*18*) large-scale brecciation and small-scale folding area; (*19*) heating and greenschist metamorphism area; (*20*) heating and low-pressure (greenstone) metamorphism area; (*21*) direction of the thrust plane rotation during warping; (*22*) direction of the thrust plane rotation in response to simple horizontal shear; (*23*) intensely metamorphosed rocks; (*24*) granulites; (*25*) greenstone rocks, amphibolites; (*26*) dike complex; (*27*) main tectonic detachment surfaces; (*28*) plastic shear.

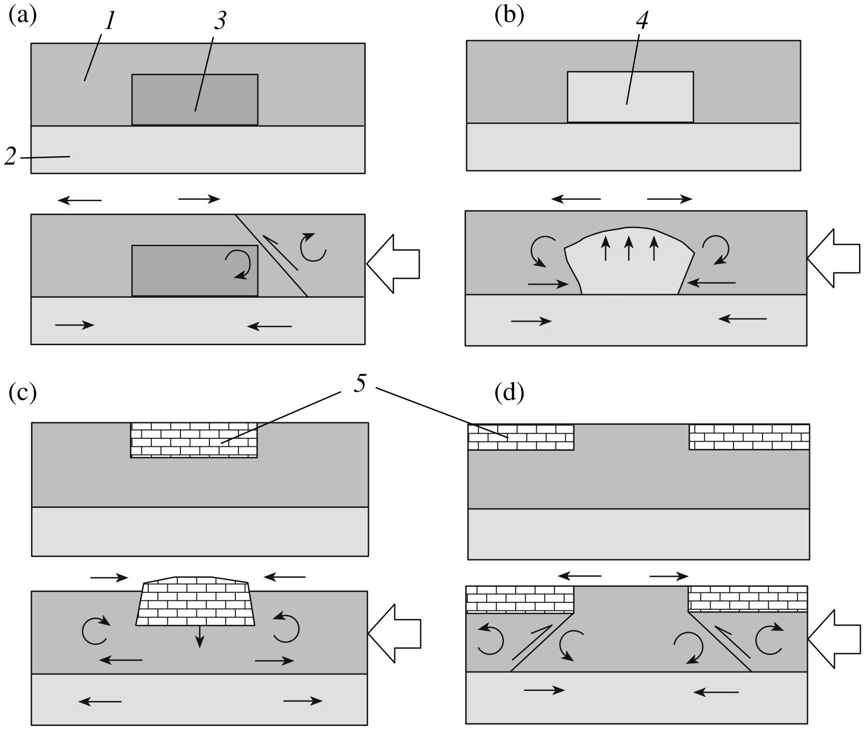

Fig. 2. Some possible scenarios for the loss of flexural stability in the rheologically layered crust: (a) “Rigid block” at the base of the upper crust; (b) “quasi-plastic block” at the base of the upper crust; (c) “sedimentary basin”; (d) “swell of the basement.” (*1*) Upper crust; (*2*) lower crust; (*3*) “rigid block”; (*4*) “quasi-plastic block”; (*5*) “sedimentary basin.”

pression stimulate brittle–ductile deformations in the upper crust and plastic deformations in the lower crust accompanied by slight heating of rocks. It is assumed that heating and decompression in deep crustal layers at the base of the tectonic wedge could provoke the formation of the magma chamber “sealed' by the stress pressure at upper levels. Thinning of the crust in the horizontal extension zone fosters the ascent of boundaries *K* and *M* relative to adjacent positive structures. The lower crust undergoes additional vertical extension in response to upward squeezing out of the upper crustal block along the system of thrusts.

Lithostructural transformation of the crust. In the case of a *positive bend*, the extension zone corresponds to cold and fissured rocks. Taking into consideration the vertical gradient of tensile stresses, this mechanism requires minimal energy for the initiation of graben (Fig. 2c). Therefore, this process is not accompanied by metamorphism. In contrast, heating of rocks in the compression zone stimulates their progressive metamorphism under elevated *PT* conditions. Some energy is consumed by reactions of dehydration, which increase the density of rocks and stimulate release of reduced fluids. The growth of temperature, as well as uniform and fluid pressures, leads to increase in the plasticity of rocks. The presence of a vertical stress gradient in the upper crust promotes the formation of plastic and quasi-plastic flows oriented toward basal parts of grabens. These flows transfer thermal energy and pressure from lower to upper levels, resulting in the appearance of dome-shaped structures and high-grade zoned metamorphism in their peripheral parts, while fluids promote granitization. The lower crust lacks the vertical stress gradient. Therefore, it becomes thicker under horizontal compression.

In the case of a *negative bend*, the upper horizons remain cold. In the underlying zone, stress generated by increase in the lithostatic load facilitates heating of rocks and their metamorphism up to the greenschist facies. Tensile settings beneath the NS are favorable for greenstone metamorphism grading into epidote–amphibolite and amphibolite metamorphism under the influence of fluids released during extension. The magma chamber located within the crust is intermittently discharged to form small and ring intrusions within the horst structure. *Thrusts* between crustal flexures undergo rotation during deformations and tend to occupy a vertical position. At the same time, the entire crust is subjected to horizontal *simple shear* (in the physical sense), which is most readily realized in plastic rocks. Therefore, simple shear at the initial stage of crustal folding is almost completely localized in the lower crust and its further development is hampered by elasticity and continuity of the upper crust, which is still unready for significant horizontal displacements. Further heating of the crust increases the plasticity of its lower horizons, and the crust undergoes more intense simple shear.

Termination of the GCF. During development of the GCF, the upper crust slips along the roof of the lower crust, while the latter slips along the surface of the upper mantle (Fig. 2d). At the same time, both slabs undergo simple shear. In the upper crust, this process results in rotation and warping of thrust planes: they are characterized by unidirectional dip and flattening with depth. In the lower crust, previously developed sectors of thinning and thickening are leveled to form tectonic detachments. The general thickening of the slab is accompanied by the formation of local inclined zones of simple shear. The heating of the upper crust increases its plastic properties and flattening under horizontal compression. The thickness of the elastic crust decreases sharply, and the crust loses its ability to transfer the stress. The bending moments disappear as the result of exhaustion of their resources. The stress pressure is leveled in positive and negative structures, and they become more similar with tectonic blocks metamorphosed in different settings. Moreover, blocks of former negative structures are less heated than blocks of positive structures. The extension regime in lower parts of negative structures is replaced by moderate horizontal compression with corresponding metamorphic transformations of rocks. In contrast, the bending stress in lower parts of contiguous blocks gives way to moderate stress pressure and slight fall of the general pressure. This is also accompanied by metamorphic transformations of rocks.

Specific features of the GCF. The elastic upper crust transfers stresses over significant distances, while the bend accumulates compression energy in relatively small rock volumes. The arch is poorly, if at all, manifested during warping. Positive and negative structures resemble large blocks (syn- and antiforms) separated by thrusts of the opposite vergence. The crust is thickened proportionally to reduction of its horizontal size. If tectonic stress is removed, crustal deformation can cease at any stage to recommence when the stress appears. Deep-seated thrusts of the opposite vergence, alternation of thickened and thinned sectors of the crust, alternation of areas subjected to greenschist and high-grade metamorphism, and other features are characteristic of *incomplete* crustal folding (Fig. 2c). The imbricate thrust structure of the crust, alternation of areas subjected to greenschist and high-grade metamorphism, intense rock deformation, and sharply manifested linearity indicate *complete* folding (Fig. 2d). The incomplete GCF is characteristic of the Urals, while the complete GCF is typical of the Belomorian belt. The folding begins from the indenter side. The area of incomplete folding is located at the front of complete folding in all cases, including the crust of the platform type. This may be interpreted as a structural paragenesis of the regional rank. The crust, which is hypothetically isotropic along the lateral direction, becomes anisotropic due to the GCF. As follows from Fig. 2, the geological evolution of a particular region may complicate strongly the GCF process therein.

CONCLUSIONS

(1) Under oriented horizontal compression, the rheologically layered crust is inevitably subjected to undulatory warping regardless of its thickness, composition, and geological history.

(2) The longitudinal warping of the crust focuses compression energy, resulting in cardinal lithostructural transformations.

(3) Evolution of the GCF during deformations promotes transformation of the structure into the imbricate thrust belt (complete folding).

(4) The removal of horizontal tectonic stresses may stop folding at any stage (incomplete folding). The resumption of tectonic stresses promotes the reactivation of crustal warping.

(5) The geological evolution of the region complicates significantly the GCF.

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