Core complex mechanics: From the Gulf of Corinth to the Snake Range

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ABSTRACT

The activity of subhorizontal décollements mapped by geologists in extensional provinces is not explained by rock mechanics principles, which predict that only steep faults can slip. These exposed décollements are therefore suspected to be inactive; they may correspond to rotated, formerly active, high-angle faults. However, growing seismological evidence of earthquakes with low-angle fault-plane mechanisms has forced us to revisit this viewpoint. Using the example of the Gulf of Corinth in Greece, we propose a mechanical model that explains how a weak, high-angle fault may form a low-angle décollement at depth. This décollement is uplifted in a second stage of extension, which allows the exhumation of a metamorphic core complex such as the northern Snake Range, Nevada.

Keywords: core complexes, décollement, extension tectonics, rock mechanics, friction, Corinth Greece, Snake Range.

INTRODUCTION

Core complexes in continental areas are highly metamorphosed rocks exhumed from mid-crustal levels to near surface during episodes of active extension. Such bodies are found mainly in previously extended orogens such as the Basin and Range in the western United States or the Cyclades in Greece. These structures are limited above by a low-angle or even horizontal décollement that separates a brittlely deformed upper plate from a ductilely deformed lower plate. The origin of these décollements has been a matter of debate since their discovery, because rock mechanics principles predict that high-angle faults may only be created under extension (Anderson, 1951; Buck, 1988). Two basic hypotheses lead to this prediction: first, one of the principal stress directions within the crust is vertical. In extension, the maximum principal stress is therefore vertical. Second, the angle between the fault and $\sigma1$ is given by $\pi/4 - \phi/2$, where ϕ is the friction angle. Because ϕ is ∼30° for rocks, the fault dip for extensional faults should be ∼60° relative to horizontal, i.e., consistent with seismotectonic observations (Jackson and White, 1989). Geomechanical models that verify these principles therefore assume that these horizontal décollements initially formed at high angles (∼60°). In this case, the faults may still be active while they are tilted if we use a domino block geometry (Davis, 1983). Alternatively, they can rotate as passive markers as soon as they become deactivated and rotate to a low angle (rolling hinge model; see Buck, 1988). However, the simple shear model violates Anderson's principles because it postulates that a décollement fault can form with a low-angle fault (i.e., <30°) crossing the crust or the entire lithosphere (Wernicke, 1981, 1985; Parsons and Thompson, 1993). Until recently, a strong argument against the simple shear model was the lack of low-angle focal mechanisms in extensional provinces (Jackson and White, 1989). However, scarce but convincing low-angle fault mechanisms have been found recently on the d'Entrecasteaux ridge, New Guinea (Abers et al., 1997), and in the Gulf of Corinth, Greece (Rietbrock et al., 1996; Bernard et al., 1997). We use here a mechanical analysis to study how such low-angle faults may form in apparent conflict with rock mechanics. We propose an evolutionary model that explains how an extensional domain such as the Gulf of Corinth may later evolve toward a highly extended core complex, e.g., such as the northern Snake Range, Nevada.

GULF OF CORINTH

The Gulf of Corinth (Fig. 1A) is an asymmetric graben that separates the Peloponnesus from northern Greece. The southern side of the basin is bounded by high-angle faults (Helike, Aigion) that have produced destructive earthquakes in the past centuries. If we assume that these faults extend to 10–15 km depth, morphological arguments based on

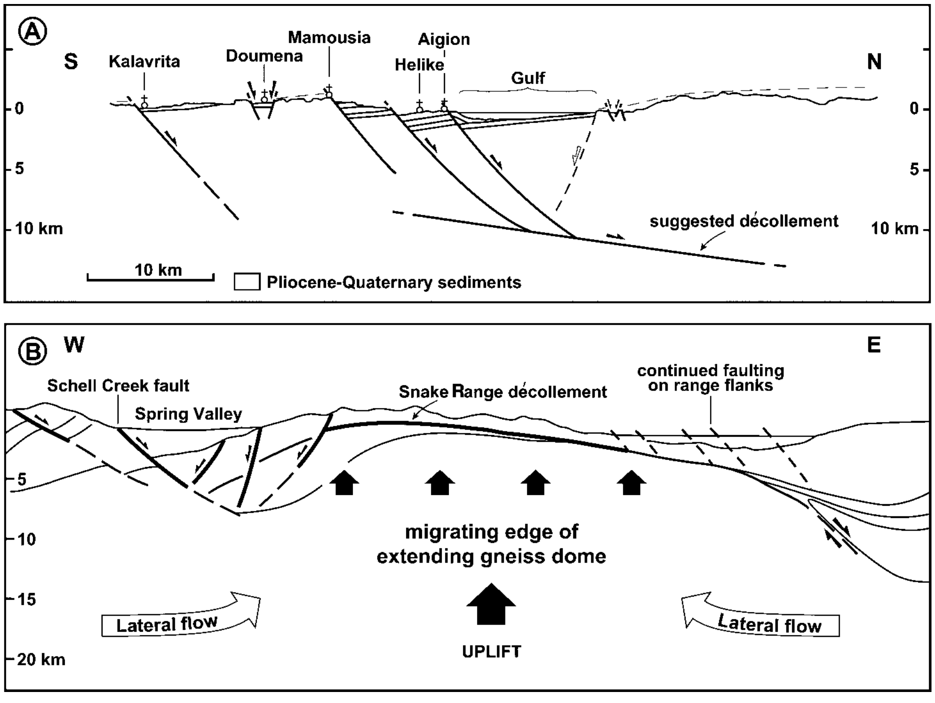

Figure 1. Two extensional structures with low-angle décollements. A: Interpretative north-south cross section of western part of Gulf of Corinth (Rigo et al., 1996). Aigion and Helike are active high-angle faults. Décollement fault beneath gulf is suggested by microseismicity analysis and low-angle fault planes (15°–30°) determined from microearthquake focal mechanisms. B: Interpretive east-west cross section of northern Snake Range fault system (Miller et al., 1999). Décollement surface is at surface level on topographic high and limits top of ductile deformation. Uniform fission-track cooling ages of 17 ± 3 Ma are found below décollement.

Geology; May 2001; v. 29; no. 5; p. 439–442; 3 figures.

footwall uplift and basin subsidence are consistent with a finite extension of 8–12 km for the rifting phase (Armijo et al., 1996). Uplift of Quaternary terraces in the southern gulf margin can be used to predict that 7 mm/yr of extension is achieved by high-angle faults (Armijo et al., 1996) with a surface dip of 50°–60°. Because a global positioning system geodetic network has been set up north and south of the basin, we know that present-day extension across the gulf ranges from 10 to 15 mm/yr (Briole et al., 2000), suggesting that high-angle faulting accounts for only 50%–75% of the entire basin opening. It is not known whether the remaining part of total extension is taken by other faults or by diffuse extension in the basin. However, focal mechanisms with fault dips between 10° and 30° have been recorded in the basin between 8 and 12 km depth, north of the high-angle faults (Rietbrock et al., 1996; Bernard et al., 1997); these data suggest that low-angle faulting is also part of the overall extension. The Gulf of Corinth therefore presents a remarkable example of an association between high-angle and low-angle active faulting during the same tectonic phase.

SNAKE RANGE

In contrast to the Gulf of Corinth, the Snake Range (Nevada, United States) fault system is not actively extending. Its present-day deformation is rather small; relative velocities are ~1 mm/yr or less, as attested to by a geodetic survey across the Basin and Range (Thatcher et al., 1999). However, this ancient orogenic zone was actively extended during Miocene time (Gans et al., 1985); it is a highly deformed metamorphic core complex (Fig. 1B), indicating that a major crustal denudation and uplift took place. This core complex is limited by a subhorizontal décollement surface crossing the topography. This inactive low-angle fault represents an ancient limit between a brittle domain above and a zone with intense ductile deformation below. Although the finite slip of the décollement is not known, it may range from 1 km to tens of kilometers. The chronology of décollement uplift is precisely provided by fission-track analysis of mylonites sampled below the décollement along east-west profiles (Miller et al., 1999). All apparent ages of the 100 °C isotherm are stacked around 17 ± 3 Ma for 40 km-length-profiles, suggesting that the core complex was uplifted synchronously along the décollement surface.

MECHANICAL MODELING

It appears from these descriptions that both the Gulf of Corinth and the Snake Range fault system bear evidence of low-angle faulting near the brittle-ductile transition. It can also be conjectured that these structures may have been created under similar boundary conditions, namely a rapid extension (a few centimeters/yr). An obvious problem is to understand whether these tectonic structures represent two end members of the same model of extension, such that a juvenile phase corresponds to the Gulf of Corinth and an evolved phase corresponds to the Snake Range. Because low-angle faulting is present and seems to be active in both tectonic structures, a more fundamental problem is to propose an alternative to the Andersonian theory.

The cornerstone of this theory is that crustal faults have mechanical properties consistent with high rock friction. This view is supported by borehole and laboratory stress measurements (Byerlee, 1978; Townend and Zoback, 2000), which suggest that an intraplate crustal state of stress may be explained with a high intrinsic friction coefficient, μ, of 0.6–0.8 and hydrostatic pore pressure. However, other geophysical observations along interplate faults such as the San Andreas fault or of active subduction zones suggest that faults may also be weak (i.e., Mount and Suppe, 1987; Wang et al., 1995), with an effective friction coefficient (0–0.1) that corresponds to low effective friction angles (0°–6°) (given the simple relation $\mu = \tan \phi$). Whatever the physical explanation of these low values, it implies that the shear stress on the corresponding fault plane is low, and therefore that one of the principal stresses in the crust is normal to the fault plane (Rice, 1992). In the case of a dipping fault, principal stress orientations cannot be aligned with horizontal and vertical directions, as postulated from Anderson's theory. As a consequence, stress rotations must occur in the crust to ensure zero shear traction on the fault surface, as shown by Melosh (1990).

Using a plane strain finite element code (Chéry and Hassani, 2000), we investigate a model in which stress and strain are controlled by a weak fault embedded in continental crust. This model (Fig. 2A) has a high-angle fault (58°) compatible with a half-graben geometry (Vening-Meinesz, 1950). Shear and normal stress are computed using a Coulomb criterion and an effective fault friction of 0.1. High strength is assumed for the upper crust, and an internal friction of 0.6. A thermally activated viscous law is taken for the middle crust (following Kirby, 1985). Because core complexes generally develop in regions of high heat flow, we assume that high temperature leads to hydrostatic stresses in the lower crust and in the mantle (Buck, 1991), which are replaced by a buoyant boundary condition. We impose a horizontal velocity of extension of 1.3 cm/yr, based on large values measured for the Gulf of Corinth and for actively deforming core complexes (Abers et al., 1997). The duration of the experiment is 0.65 m.y. in order to ensure 8 km of extension; negligible thermal transfer occurs during this short period of extension. An isothermal model is therefore assumed. A high differential topography arises from the high-angle fault model (Fig. 2B).

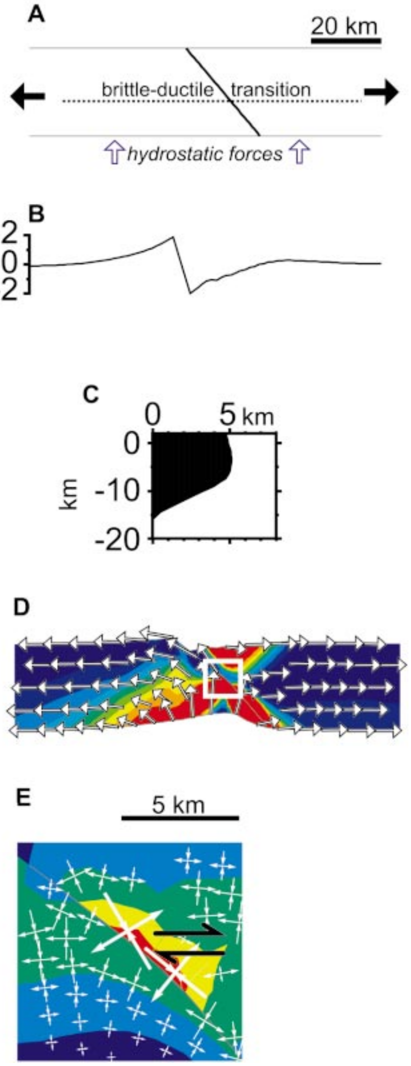

Figure 2. High-angle fault model. A: Crustal cross section is submitted to gravity and to horizontal velocity of extension. Weak high-angle fault cuts crust. Brittle-ductile transition corresponds approximately to 350° isotherm. B: High differential topography progressively rises during 8 km of finite extension due to fault slip and crustal rotation. C: Horizontal fault slip versus depth. Fault slip is constant in upper crust and progressively vanishes below 10 km at brittle-ductile transition. D: Strain develops in response to extension and fault rotation (deformed zones in red). E: Maximum deviatoric stress of 250 MPa (red) occurs at 10 km depth in hanging wall. This location also corresponds to stress-axis rotation to 45° relative to vertical and horizontal directions. Black arrows represent orientation of maximum shear stress, which is compatible with low-angle faulting.

Footwall topography is related to crustal bending and corresponds to a progressive fault rotation at a rate of 1°/km of extension. This fault motion is compatible with terrace uplift on the south margin of the Gulf of Corinth described by Armijo et al. (1996). Hanging-wall subsidence also results from this rotation. The horizontal component of the fault slip (Fig. 2C) reaches 5 km in the upper crust (62% of extension) and decays rapidly in the low-viscosity medium below (Fig. 2D). The stress field (Fig. 2E) reflects the interaction between the crustal rheology and this weak fault: stress directions are horizontal and vertical far from the fault (according to Anderson's theory), but tend to align with the fault dip in the hanging wall within 5 km of the fault. As maximum shear traction is oriented at 45° to principal stress direction, the shear traction in the hanging wall is therefore subhorizontal and can promote low-angle fault formation. Although these stress directions result from a finite extension of 8 km, as occurred in the Gulf of Corinth, we emphasize that this stress rotation takes place from the very beginning of extension. Therefore, this stress state is not related to a progressive crustal bending. Rather, principal stress directions are constrained by the friction conditions that require a low shear traction on the fault plane from the beginning of extension. This finding is consistent with the results of Melosh (1990), that were obtained for a frictionless fault and for an infinitesimal extension. In addition, because our model includes a progressive rotation of the high-angle fault, it may explain why fault dip histograms of normal-faulting earthquakes display a mode near 45° (Jackson and White, 1989), instead of a value of 60°, as it would be predicted by Anderson's theory. In the light of our model, normal faults may initially develop at ~60° dip, and coalesce into a major normal fault during their progressive rotation toward 30°–45° dips, as suggested by Thatcher and Hill (1991). In contrast, the incipient formation of all normal faults at ~45° is not supported by Anderson's theory and our numerical model.

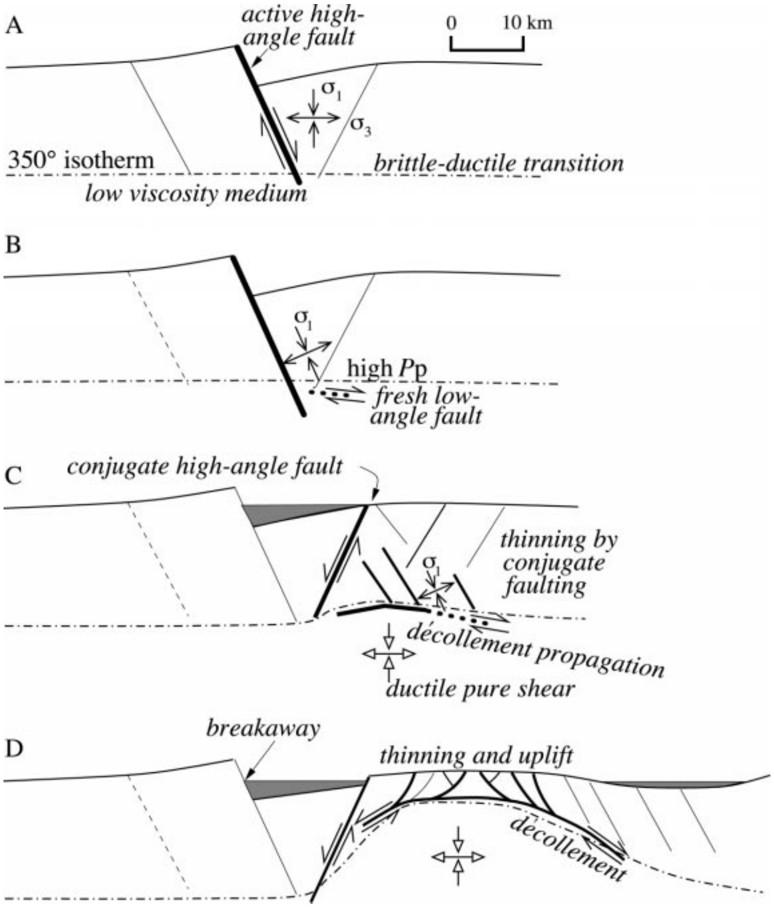

Figure 3. Evolutionary model of core complex. A: Half graben, or Andersonian stage: stress orientation is not perturbed, because of high fault friction. B: Gulf of Corinth stage: elevated pore pressure P_p leads to low effective friction that forces σ_1 to be fault parallel in footwall. Low-angle fault forms and is ready to act as décollement. C: Décollement propagation stage: upper crust is thinned above décollement by normal faulting. New high-angle faults control décollement propagation and help crustal exhumation. D: Snake Range stage: major and rapid horizontal extension (20–40 km in a few million years) raises isostatically and isothermally. Décollement develops as antiform that migrates toward shallow depths (0–4 km). Temperature reequilibrates to regional values after end of extension, resulting in uniform cooling ages below décollement, as observed in northern Snake Range.

INITIATION OF A DÉCOLLEMENT

On the basis of stress rotation shown by our model (a weak, high-angle fault), we suggest that a high-angle fault may create a décollement fault at depth. If we assume that the crust is a fractured medium at all scales, without strong initial heterogeneity, the following mechanical processes may occur during extension (also see Fig. 3).

The initial state of stress is Andersonian, with a vertical maximum stress σ_1 and a horizontal minimum stress σ_3. High rock friction and hydrostatic pore pressure correspond to an effective friction of 0.6 in the crust. A high-angle normal fault then develops due to a small decrease of fault friction and leads to formation of a half graben (Fig. 3A). As extension develops, trapped fluids between quasiimpermeable fault walls increase pore pressure P_p, as suggested by Rice (1992) for the San Andreas fault. Effective fault friction is given by $\mu_{eff} = \mu(1-P_p/\sigma_n)$, where μ is the intrinsic rock friction and σ_n is the normal stress. Because P_p may increase to σ_3 without hydrofracturing surrounding rocks, low effective friction may occur. This weak fault results in a low shear traction along the fault plane and forces the stress axes to rotate in the crust. In the simple case where shear traction vanishes, σ_1 rotates from 90° (vertical) to the fault dip angle, which is typically 45°–60°. In addition to stress rotation, a mean stress increase in the hanging wall leads to high pore pressure near the fault tip in a way suggested by Axen (1992). The combination of high differential stress, stress rotation, and high pore pressure favors the formation of a fresh fault at a depth of ~10 km (Fig. 3B). This new fault forms at 45°–60° to σ_1 orientation, generating a low-angle fault plane. This model is compatible with seismotectonic observations of the Gulf of Corinth, because it explains how both high-angle and low-angle faults may be active in the same geological structure.

We propose that a low-angle fault created at a mid-crustal level may evolve as a décollement fault bounding a core complex such as the northern Snake Range Miocene fault system. Fission-track thermochronology of the Snake Range indicates that the core complex has been uplifted through the upper crust in a short period of time, probably <2–3 m.y.; therefore, we need a model that rapidly raises the mid-crust décollement as a whole. Because the horizontal extension of the Snake Range décollement is as large as 20 km, a mechanism is also needed to explain the décollement growth through the middle crust and its final uplift as a topographic high.

We have argued that high-angle faulting of the master fault is responsible for décollement formation; we suggest also that the development of intense faulting of the hanging wall triggers both décollement propagation and uplift, as suggested in Figure 3C. This fault system, which is limited by the conjugate high-angle fault of the basin, is just above the décollement. As extension develops, these faults weaken because of fluid overpressuring mechanics as described by Rice (1992; see also Axen, 1992), leading to stress rotation, as previously discussed. As a consequence, the décollement below propagates along the brittle-ductile transition in association with upper crustal faulting. These high-angle faults may flatten and root into the brittle décollement, as suggested by Gans et al. (1985). Because the fault system thins, owing to extension, isostatic uplift exhumes the décollement, while the activity of the conjugate high-angle fault creates a topographic high above the metamorphic dome (Fig. 3D). Beneath the décollement, ductile levels extend mainly by pure shear. This rapid deformation stretches the isotherms, weakens the uplifted zone, and enlarges the metamorphic body. Assuming an uplift rate of 5 mm/yr for the low-angle fault, the core complex may therefore be exhumed in 2 or 3 m.y. from mid-crustal level to subsurface depth. Only a little erosion of the Snake Range is needed to expose the décollement in its present-day position. The end of this extensional phase allows the system to thermally reequilibrate, the result being the moderate heat-flow variations now observed in the Basin and Range (Sass et al., 1994).

Based on rock mechanics principles and mechanical modeling, our model of core complex formation is markedly different from the simple shear model, the domino block model, or the rolling hinge model. Although we used the specific examples of the Gulf of Corinth and the Snake Range fault system in devising it, it may be used as a generic model for other core complexes that present a structural association between a horizontal décollement and a graben structure, e.g., as for the Red Sea décollement in Eritrea (Talbot and Ghebread, 1997) or other Basin and Range core complexes.

ACKNOWLEDGMENTS

Because of the speculative nature of this study, I sought the opinions of many of my colleagues. I especially thank Daniel Stockli, who showed me in the field the tectonic features of the Snake Range. I benefited from many discussions with Pierre Briole and Hélène Lyon-Caen about the Gulf of Corinth. Laurent Jolivet also gave the idea that the Gulf of Corinth might be a core complex in its juvenile stage. Francis Lucazeau, Jean-François Ritz, and Michel Séranne provided critical comments on the manuscript. I thank Wayne Thatcher and Roger Buck for their reviews.

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Manuscript received September 25, 2000
Revised manuscript received January 12, 2001
Manuscript accepted January 29, 2001

Printed in USA