

Gravitational collapse of the continental crust: definition, regimes and modes

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Abstract

The concept of gravitational collapse has fundamentally improved our understanding of orogenic processes. This concept has its roots in pioneers' works, such as those of Jeffreys, van Bemmelen, Bucher and Ramberg, who were among the first to recognise the importance of gravity in the evolution of mountain belts. The development of this concept slowed down during the late 1960s and the 1970s before reemerging in the 1980s. Gravitational collapse corresponds to the decay of lateral contrast in gravitational potential energy that builds up during lithospheric deformation. When the forces that support this anomaly (i.e., tectonic forces and the strength of both the deformed and surrounding lithosphere) decrease, the gravitational potential anomaly may relax. Depending on the sign of the anomaly, two fundamental regimes of gravitational collapse can be defined. During divergent gravitational collapse, an excess in gravitational potential energy drives crustal material away from the deformed lithosphere. Divergent collapse is the regime that may affect the thickened crust. In contrast, during convergent gravitational collapse, a deficit in gravitational potential energy drives crustal material towards the deformed lithosphere. This regime can be expected to occur following thinning of the continental crust. For each regime, two end-member modes of collapse with contrasted characteristics are defined depending on the behaviour of the lithosphere surrounding the deformed domain. When the surrounding lithosphere is fixed (fixed-boundary collapse), collapse occurs through a transfer of gravitational potential energy from the elevated regions towards the low lands. This transfer is accommodated by a combination of gravitational sliding of the brittle crust and horizontal spread of the lower crust. In orogenic domains, fixed-boundary divergent collapse implies the lateral growth of the orogenic domain at the expense of the surrounding lithosphere. In contrast, when the surrounding lithosphere is free to move (free-boundary divergent collapse), the thickened crust is homogeneously thinned without transfer of gravitational potential energy towards the forelands. © 2001 Published by Elsevier Science B.V.

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1. Introduction

The discovery of regions of surface extension in zones of active convergence, such as the Andes or the Himalayas (Molnar and Tapponnier, 1975, 1978; Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Burg et al., 1984; Burchfiel and Royden, 1985; Sébrier et al., 1985), led to a reassessment of the role of gravity in the evolution of mountain belts. Plate tectonics provides no direct explanation for such deformation and, consequently, gravity-driven flow of orogenic crusts under their own weight was proposed (England, 1982; Molnar and Chen, 1982, 1983; Coney and Harms, 1984; McClay et al., 1986; Dewey, 1988; Ménard and Molnar, 1988; Molnar and Lyon-Caen, 1988; England and Houseman, 1989). This concept, referred to as gravitational collapse, assumes that gravitational potential energy stored in thickened crust during convergence can be released via lateral spreading, thus triggering extension and thinning of the thickened crust and shortening and thickening of the foreland (e.g., Dewey, 1988). During the last decades, the concept of orogenic collapse has gained momentum. It provides a coherent framework to many processes that occur in both the foreland and hinterland of mountain belts, in particular, but not only, in the waning stages of their orogenic evolution. However, owing to the lack of clear terminology and definitions, there is still confusion about what gravitational collapse is, how it relates to other types of gravitational driven flow and what its structural expressions are. Indeed, a concept, such as “synconvergence spreading” (e.g., Gapais et al., 1992), does not fit easily with the concept of collapse, as it suggests that gravity-driven flow may occur during convergence and thickening. Gravitational collapse is very often referred to as “extensional collapse”, which strongly suggests that collapse is invariably associated with surface extension. However, a growing number of studies points towards channelled lateral flow in the lower crust, a mechanism that could accommodate collapse without triggering surface extension (Bird, 1991; Royden and Burchfiel, 1995; Royden et al., 1997). Therefore, a large number of terms have been introduced to describe the gravity-driven flow that counteracts crustal thickening. Indeed, extensional collapse, orogenic collapse, intraorogen collapse, gravitational collapse, postthickening collapse, postthickening

extension, postorogenic collapse and late-orogenic collapse, have all been used in a variety of contexts to name the processes that control gravitational reequilibration of thickened crusts.

This paper first presents a brief history of the emergence of the concept of gravitational collapse. An attempt is then made to define the concept in broad physical terms and to separate it from other gravity-driven processes. We emphasise that gravitational collapse may not only affect convergent systems, but also stretched lithospheres. From this, we propose to define two fundamental collapse regimes: divergent and convergent gravitational collapse. Gravitational collapse is a mass transfer process and, therefore, a space problem must be solved. Depending on the behaviour of the system's boundaries, we suggest that two end-member modes of gravitational collapse, that are applicable to both convergent and divergent regime, can be defined.

2. Evolution of ideas on the role of gravity on tectonic processes

Our aim is not to provide an exhaustive review of the work published so far on the concept of gravitational collapse, but to mention a number of papers that have helped the emergence and the acceptance of the concept.

About a century ago, the discovery of large displacements in mountain belts led to the idea that significant horizontal compression forces were required to build mountains (Bertrand, 1897; Termier, 1907; Argand, 1924). At the time, the best explanation was provided by the contraction theory related to secular cooling of the Earth and the formation of geosynclines and geanticlines (Suess, 1885). In this context, the concept of gravity tectonics was already applied to regional deformation, in particular to the formation of folds and thrusts in the foreland zones of mountain belts (De Wijkerslooth de Weerdesteyn, 1934). It was then proposed that the formation of large domes (Eskola, 1948) due to buoyant exhumation of magmatic rocks, or the buoyant uplift of the gneissic core of mountain belt was responsible for the downslope gliding of supracrustal nappes (Steinman, 1907; Bucher, 1956; van Bemmelen, 1960, 1965, 1966).

The physical assessment of the deep structure of mountain belts and the notion of isostatic compensation (Airy, 1855) brought the idea of lateral variations of gravitational potential energy in the crust across mountain belts (Jeffreys, 1929; Haarmann, 1930; Cloos, 1936; Goguel, 1947; van Bemmelen, 1954). Accordingly, a number of authors described the formation of large crustal nappes sliding from the hinterland to the forelands of orogenic belts, in terms of flow of material away from zones of high gravitational potential (e.g., Steinman, 1907; Goguel, 1946; Gignoux, 1948; van Bemmelen, 1954; Bucher, 1956). Along with gravitational sliding (translation of supracrustal rocks along an unstable slope), gravitational spreading (the horizontal spreading and vertical shortening of a pile of nappes under their own weight) was debated as a mean to reduce gravitational potential energy (Jeffreys, 1929; Wunderlich, 1953; Bucher, 1956; van Bemmelen, 1960; Kehle, 1970; Price and Mountjoy, 1970; Price, 1973). Although most studies restricted gravity-driven flow to supracrustal nappes, Jeffreys and van Bemmelen were among the first authors to consider gravity-driven flow at the scale of an entire thickened crust. Indeed, in his book “Mountain Building”, van Bemmelen (1954) distinguished a primary tectogenesis or orogenesis, from a secondary tectogenesis or gravitational tectogenesis. The primary tectogenesis is a phase of mountain building associated with the development of lateral variations of gravitational potential energy. During the gravitational tectogenesis, mountain belts are destroyed by gravitational flow in order to reduce lateral variations of gravitational potential energy: “mountains collapse, like idols on feet of clay”. van Bemmelen also considered the role of crustal root weakening, mainly related to partial melting, and he introduced various modes of gravitational tectogenesis including: (1) epidermal gravitational tectogenesis related to surface processes; (2) dermal gravitational tectogenesis associated with translation of upper crustal nappes, accommodated by extension in the high land and compression in the low land; (3) bathydermal gravitational tectogenesis characterised by lateral sliding of upper crustal material coeval with ductile horizontal flow of a partially molten crustal root; and (4) subcrustal gravitational tectogenesis in which horizontal ductile flow of the weak crustal root is accompanied by passive motion of the upper crustal (dermal) cap.

Between the late 1960s and the late 1970s, earth scientists focused their attention on testing the plate tectonics theory. In this context, the emphasis was redirected on horizontal compression and the role of gravity on crustal deformation was neglected. Nevertheless, during this period a few authors refined the assessment of the force balance in the crust and lithosphere, pointing out that gravity and the lateral variations of gravitational potential energy could drive tectonic processes (Ramberg, 1966; Artyushkov, 1973; Ramberg, 1981). In his paper “Diapirism and gravity collapse in the Scandinavian Caledonides”, Ramberg (1980) confirmed the result of an early analogue experiment from Bucher (1956), that showed that horizontal displacement of thrust sheets in the forelands could be linked to the horizontal spreading and vertical shortening of a pile of supracrustal nappes in the hinterland. This tectonic process was recognised to be associated with a transfer in gravitational potential energy (PE: the integral of the product between weight and height above a reference level) from the hinterland towards the forelands. Lateral contrasts in gravitational potential energy (ΔPE) are relaxed by spreading. Ramberg (1980) referred to this tectonic process as gravitational collapse, which is by all means similar to the earlier concept of gravitational spreading (e.g., Wunderlich, 1953; van Bemmelen, 1954, 1960; Bucher, 1956). Ramberg emphasised that in contrast to downhill sliding of rock masses along an unstable slope (gravity sliding), gravitational collapse of nappes is only possible if the rocks are weak enough to sag and spread under their own weight.

After two decades of horizontal contractional tectonics and the general acceptance of plate tectonics, the discovery of surface extension in the same direction as compression driven by active lithospheric plate convergence (Dalmayrac and Molnar, 1981; Molnar and Chen, 1983; Burg et al., 1984; Burchfiel and Royden, 1985; Sébrier et al., 1985; Molnar and Lyon-Caen, 1988) initiated a dramatic reassessment of the role of gravity on tectonic processes. England (1982) and Molnar and Chen (1982, 1983) suggested that extension, until then described in the upper part of the crust only, could in fact affect the entire crust. Molnar and Chen (1983) proposed that gravity-driven extension in the High Andes of Peru and in the Basin and Range province could respectively represent a more youthful and a more advanced stage than extension in Tibet.

Studies in metamorphic core complexes of the North American Cordillera (Armstrong, 1972, 1982; Coney, 1979, 1980; Davis, 1980; Wernicke, 1981; Miller et al., 1983) and in the Aegean domain (e.g., McKenzie, 1972; Berckhemer, 1977; Le Pichon, 1982) provided important insights into the mechanisms accommodating crustal extension and the elaboration of the concept of orogenic collapse. Since then, gravitational collapse has been applied to many recent and ancient orogenic domains (e.g., Coney and Harms, 1984; McClay et al., 1986; Norton, 1986; Ménard and Molnar, 1988; Platt and Vissers, 1989; Ratschbacher et al., 1989). In the mean time, numerical modelling was central in the development of the concept of gravitational collapse (England and Houseman, 1988, 1989; Gaudemer et al., 1988; Block and Royden, 1990; Bird, 1991). England and Houseman (1988, 1989) proposed that the physical factors that can result in extension parallel to convergence fall into two categories: those involving changes to the boundary conditions (e.g., the decrease in convergent velocity) and those involving changes in the potential energy (e.g., convective thinning of the thermal boundary layer). They emphasised that the reduction in strength of an elevated region in front of a convergent boundary leads to increased contractional strain rates rather than extension. The reintroduction of gravity as a force able to drive tectonic processes provides an elegant alternative to plate tectonics to account for features such as extension superimposed on ongoing convergence, rapid exhumation of high-grade rocks in the hinterland of orogenic belts, formation of intramontane sedimentary basins (Coney and Harms, 1984; Dewey, 1988; Ménard and Molnar, 1988; Van Den Driessche and Brun, 1989; Echtler and Malavieille, 1990; Malavieille et al., 1990; Malavieille, 1993), low-pressure high-temperature metamorphism synchronous with extension (Platt and England, 1994) and the seismic layering and rejuvenation of the lower crust (Rey, 1993; Costa and Rey, 1995), to name a few.

In the last decade, the literature on gravitational collapse has dramatically expanded and, in some cases, with an overzealous reference to this process. Recent studies (Jones et al., 1996; England and Molnar, 1997; Flesch et al., 2000) have emphasised that two independent stress fields intervene in lithospheric deformation. One is related to the relative displacement of neighbouring plates, the second is

related to lateral variation in gravitational potential energy. Indeed, only the superimposition of both stress fields can successfully account for the wide variety of strain rates and tectonic regimes observed in the western United States (Jones et al., 1996; Flesch et al., 2000). For instance, the present-day northwest extension direction in the Basin and Range results from the superimposition of: (1) a north–south oriented tensile deviatoric stress field produced by an excess in gravitational potential energy in that region and (2) a west–northwest tensile deviatoric stress field produced by the north-westerly displacement of the Pacific plate relative to the North American plate (Flesch et al., 2000). More interestingly, gravitational potential energy orients compressional deviatoric stresses at high angle to the California coastlines (Flesch et al., 2000) where contractional deformations in the Coast Ranges and Transverse Ranges are consistent with the deficit in gravitational potential energy found there (Jones et al., 1996). These studies, in agreement with the work of Artyushkov (1973) that already pointed out that stretched lithospheres are under horizontal compressive stresses due to variations in crustal thickness, strongly suggest that variation in gravitational potential energy may not only drive extension, but also contraction.

3. Gravitational collapse: a definition

A formal definition of the concept of gravitational collapse can be derived from the work of van Bemmelen (1954), Bucher (1956) and Ramberg (1980). van Bemmelen introduced the concept of transition from a phase during which lateral contrasts in gravitational potential energy develop to a phase during which lateral contrasts are relaxed. Bucher and Ramberg brought in the distinction between gravitational sliding and gravitational spreading and, therefore, the necessity to separate gravity-driven displacement along unstable slopes from gravity-driven ductile flow. In addition, Artyushkov (1973), Jones et al. (1996) and Flesch et al. (2000) showed that variation of gravitational potential energy may not only produce tensile, but also compressive stresses, promoting both horizontal extension and shortening. Consequently, it does not appear necessary to link the definition of gravitational collapse to any particular tectonic regime.

On that basis, we propose that the concept of gravitational collapse *sensu stricto* can be defined as *the gravity-driven ductile flow that effectively reduces lateral contrasts in gravitational potential energy*. Applied to a region with an excess of gravitational potential energy, this flow will drive extension following a phase during which gravitational potential energy has been stored. In contrast, gravity-driven flow will drive contractional deformation in regions having a deficit in gravitational potential energy with respect to their surroundings.

In agreement with Bucher and Ramberg, the definition proposed excludes surface mechanisms, such as erosion, landslide and gravity sliding from the concept of collapse *sensu stricto*. One may argue, however, that erosion, landslide and gravity sliding may contribute actively to the effective reduction of lateral contrasts in gravitational potential energy. An extended definition of gravitational collapse could, therefore, also include “erosional collapse” (a term initially introduced by Avouac and Burov, 1996) which, in addition to erosion, also comprises landslide and gravity sliding.

This definition has important consequences that need to be emphasised. First, it links gravitational collapse to an effective reduction of the contrast in gravitational potential energy. As long as the combination of gravity-driven flow and plate boundary-related flow implies that more potential energy is stored in the lithosphere, there is no gravitational collapse even if gravity-driven flow is very active. The gravity-driven flow that merely opposes thickening during convergence does not constitute a form of gravitational collapse. Furthermore, the proposed definition makes no reference to surface deformation. Therefore, the use of terms, such as “extensional collapse”, should be restricted to situations where collapse is accompanied by horizontal surface extension, which may not be always the case.

4. Mechanics of gravitational collapse

In this section, we discuss the origin of the force that drives gravitational collapse and we present two contrasted ways to appraise this force and its consequences in terms of deformation. Several discussions on the physics of gravitational collapse have been proposed (Sonder et al., 1987; Molnar and Lyon-

Caen, 1988; England and Houseman, 1989; Zhou and Sandiford, 1992; Platt and England, 1994). We emphasise here that most of the gravity-driven flow that tends to reduce the lateral contrast in gravitational potential energy occurs in the crust, whereas most of the gravity-driven flow taking place in the mantle tends to enhance the action of plate boundary forces.

The density profile and the rheological profile are essential in the appraisal of gravitational collapse. On one hand, the gravitational force that drives collapse is related to lateral contrasts in density (Fleitout and Froideveaux, 1982; Molnar and Lyon-Caen, 1988). In the other hand, its consequence in terms of strain rate is related to (but not only) the strength profile of the deforming lithosphere. Indeed, when the strength of the deforming lithosphere is the only force that opposes collapse, it is the gravitational force to strength ratio that controls the rate of collapse. Assuming that the continental lithosphere is a layered system with respect to viscosity and density, one can expect the gravitational force to strength ratio to vary from one layer to the next. The extent to which the different layers are mechanically coupled is certainly one of the least understood aspects of lithosphere deformation. One approach to assess lithospheric deformation is based on the viscous thin-sheet approximation that involves considering stresses and strain rates in terms of their vertical average through the lithosphere (England and McKenzie, 1982, 1983). This approach is appropriate where the horizontal dimension of a deforming region is large compare to the thickness of the lithosphere (Sonder and England, 1986). However, because of the lithosphere layering, one might expect the gravitational force and its consequence in terms of strain rate, to show significant variations throughout the lithosphere. Gravity-driven flow could, therefore, occur preferentially in weak channels, such as the lower crust (e.g., Block and Royden, 1990; Bird, 1991; Buck, 1991; Wdowinski and Axen, 1992; Royden et al., 1997; McKenzie et al., 2000). This is illustrated in Figs. 1 and 2 where the profile of the difference in lithostatic pressure underneath a deformed and undeformed lithosphere column is compared to the strength profile of a thickened (Fig. 1) and thinned lithosphere (Fig. 2). Following the thin-sheet approximation, disregarding the flexural stresses induced by the elastic behaviour of the lithosphere and assuming local isostatic compensation, the grav-

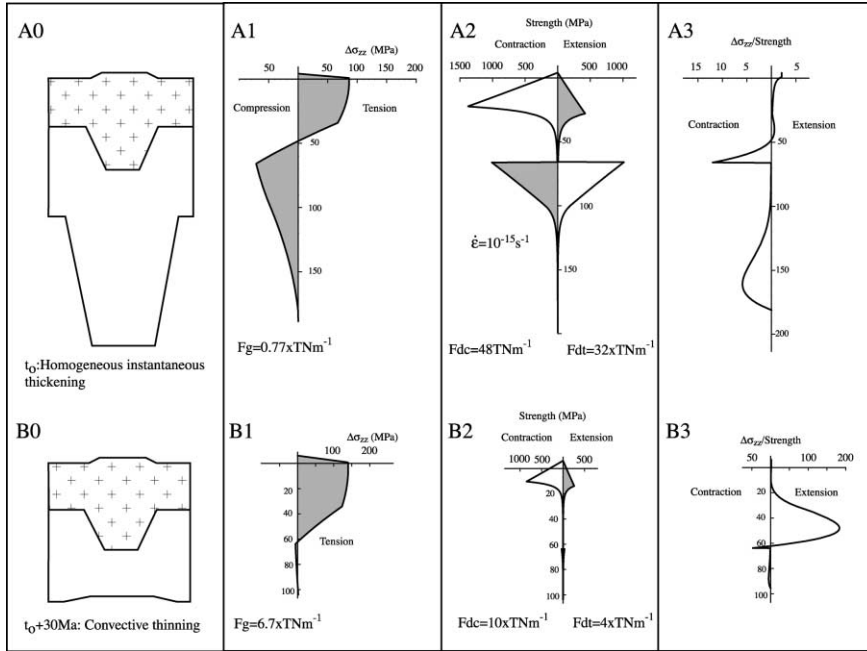


Fig. 1. Comparison between the gravitational force (F_g) and the strength of the lithosphere, after instantaneous thickening (A0 to A3), and following convective thinning occurring 30 Ma after the end of convergence (B0 to B3). The shaded regions in A1 and B1 represent the driving gravitational force, whereas the shaded regions in A2 and B2 represent the resistive force. We used for the mantle a density profile with dependence in temperature and pressure, and for the crust, a temperature sensitive density profile with an increase in density with depth. For the strength profile, we have assumed a Brace and Kohlstedt's rheological profile (Brace and Kohlstedt, 1980). The reference lithosphere column is assumed to be in isostatic and mechanical equilibrium with a mid-ocean ridge defined by an asthenospheric column with 3600 m of water above it (Le Pichon, 1982; Lachenbruch and Morgan, 1990; Houseman and England, 1986). A Crank–Nicholson finite difference scheme was used for the treatment of transient geotherms, assuming a constant heat flow at the base of the lithosphere. See text for further comments.

itational force (F_g) per unit length, which two columns of lithosphere apply onto one another, is equal to their contrast in gravitational potential energy (ΔPE). The difference in gravitational potential energy is mainly related to the deflection of density interfaces, such as: the surface of the lithosphere, the Moho and the base of the lithosphere. It is given by the difference between the integrals of the vertical stress profile (i.e., the lithostatic pressure, $\sigma_{zz}(z)$) down to a compensation level, L , beneath the lithosphere. With the depth, z , increasing downward from an origin at sea level:

$$F_g = \Delta\text{PE} = \Delta \left[\int_L^S \sigma_{zz}(z) dz \right] \\ = \Delta \left[\int_L^S \left(\int_z^s \rho(z') g dz' \right) dz \right], \quad (1)$$

where $\rho(z')$ is the density profile, g is the gravitational acceleration and z' is the integration variable. S represents either the elevation of the reference or the deformed lithosphere whichever is higher; L is either the bottom of the reference lithosphere or that of the deformed lithosphere whichever is the deepest. The net gravitational force is then compared to the resistive force to determine the rate of the gravity-driven flow. The resistive force always includes the integrated strength of the deformed lithosphere. It may also include the tectonic force (if it opposes the net gravitational force) and the integrated strength of the surrounding lithosphere. Indeed, in an orogenic domain under tensile gravitational force, the gravity-driven flow must be accommodated by either the thickening of the surrounding undeformed lithosphere, or by its passive displacement. Depending on the mechanism that accommodates collapse, the spreading rate will be buffered by either the strength

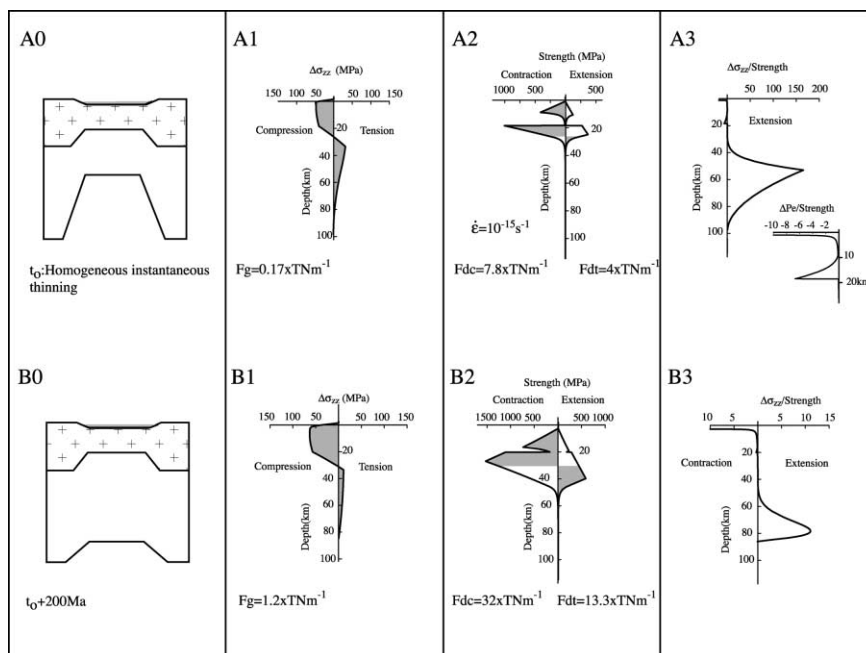


Fig. 2. Comparison between the gravitational force (F_g) and the strength of the lithosphere, after instantaneous stretching (A0 to A3) and following thermal relaxation (B0 to B3). See comments in text.

in contraction of surrounding lithosphere, or the strength in extension of the thickened lithosphere.

After instantaneous thickening by a factor 2 (which we assume for simplicity to be homogeneous), the net gravitational force calculated from Eq. (1) (the surface area of the shaded region in graphs A1) is compressive and rather small ($0.77 \times 10^{12} \text{ N m}^{-1}$) compared to the integrated strength in contraction of the thickened lithosphere ($48 \times 10^{12} \text{ N m}^{-1}$, F_{dc} in Fig. 1, B2). The positive (therefore, tensile) gravitational force in the crust balances an equivalent, but negative gravitational force in the mantle (Fig. 1, A1). Following the thin-sheet approximation, no gravity-driven flow should occur. However, in the lower crust and the lower part of the lithosphere mantle, the local gravitational force is a few times larger than the local strength. This is shown on Fig. 1, A3, where the ratio $\Delta\sigma_{zz}/\text{strength}$ is plotted against the depth. One may, therefore, expect, at least locally, gravity-driven flow to occur and possibly a mechanical decoupling due to the opposite forces that act across the ductile lower crust. After convective thinning, which we assume to occur 30 Ma after convergence, the contribution of the

lithosphere mantle to the net gravitational force decreases, whereas that of the crust increases (Fig. 1, B1). The net gravitational force is in tension ($6.7 \times 10^{12} \text{ N m}^{-1}$) and larger than the integrated strength in extension of the lithosphere ($4 \times 10^{12} \text{ N m}^{-1}$, F_{dt} in Fig. 1, B2). If collapse is accommodated by the passive displacement of the surrounding lithosphere, one may expect widespread gravity-driven flow to occur, in particular in the lower crust where F_g is two orders of magnitude larger than the local strength (Fig. 1, B3). However, collapse can be impeded by the strength in contraction of the surrounding lithosphere that may confine the orogenic domain.

In Fig. 2, we consider what happens during lithospheric thinning. After instantaneous homogeneous thinning, during which the thickness of the lithosphere and that of the crust are halved (Fig. 2, A0), the net gravitational force is compressive ($0.17 \times 10^{12} \text{ N m}^{-1}$), but is smaller than the integrated strength in contraction of the thinned lithosphere ($7.8 \times 10^{12} \text{ N m}^{-1}$). Here again the gravitational force acting on the crust balances that acting on the mantle. According to the thin-sheet approximation, no gravity-driven flow

should occur. In the basin and the lower crust, however, the local gravitational force is compressive and largely exceeds the local strength (Fig. 2, A3). This might trigger the inversion of the basin and the shortening of the lower crust. In contrast, the local gravitational force is tensile in the mantle and, although small, up to 2 orders of magnitude larger than the local strength.

After thermal relaxation over 200 Ma (Fig. 2, B0), the contribution of the lithosphere mantle to the net gravitational force has dramatically decreased, whereas that of the crust has increased. The net gravitational force is still compressive (1.2×10^{12} N m⁻¹), but smaller than the integrated strength in contraction of the thinned lithosphere (32×10^{12} N m⁻¹). In the basin, however, the local gravitational force still largely exceeds the local contractional strength (Fig. 2, B3). It is interesting to note that throughout both stretching and thermal relaxation, the sedimentary basin is under horizontal compressive stress. Should a weak layer exist at the base of the basin, thus effectively decoupling the basin from the basement, one may expect the gravitational force to be strong enough to trigger shortening and inversion of the basin.

Figs. 1 and 2 confirm that, because of the layered structure of the lithosphere, the gravity-driven flow can vary largely, not only in magnitude, but also in direction throughout the lithosphere. Consequently, the gravity-driven flow might not oppose plate boundary forces everywhere in the lithosphere. For instance, the gravitational force acting on most of the mantle underneath a thick crust (Fig. 1, A1 and A2) and a thin crust (Fig. 2, A1 and A2), promotes further horizontal shortening and extension, respectively. This, therefore, enhances the action of plate boundary forces in increasing the lateral contrasts in gravitational potential energy. In contrast, following thickening or thinning of the crust, the gravitational force which is applied to most of it opposes the action of plate boundary forces, promoting the reduction of gravitational energy and, therefore, collapse. It seems, therefore, justified to argue that, in general, the gravity-driven flow that may eventually reduce lateral contrasts in gravitational potential energy occurs in the crust. Consequently, we will thereafter focus our discussion on the gravitational collapse of the continental crust.

5. Regimes of gravitational collapse

Two fundamental regimes of gravitational collapse can be distinguished depending on the sign of the gravitational potential energy contrast between deformed and nondeformed crust. When an excess in gravitational potential energy is introduced during deformation (positive perturbation), the gravitational collapse is divergent: particles move away from the deformed domain. This regime develops during the collapse of thickened continental crust. In contrast, when a deficit in gravitational potential energy is introduced during deformation (negative perturbation), the gravitational collapse is convergent: particles move towards the thinned domain. Regions of negative gravitational potential energy have been reported in the southwestern United States, including the Great Plains, the Coast Ranges and the Transverse Ranges, the last two showing signs of active contractional deformation (Jones et al., 1996; Flesch et al., 2000). Although not defined as such, convergent gravitational collapse has been described by several authors that have investigated flow in the lower crust during heterogeneous crustal extension affecting a crust of normal thickness (Block and Royden, 1990; Buck, 1991; Wdowinski and Axen, 1992; Kaufman and Royden, 1994). In these studies, the lateral contrast in gravitational potential energy created by a heterogeneously thinned upper crust drives the lower crustal flow towards the thinned domain, effectively reducing lateral contrast in gravitational potential energy. It remains to be proven, however, that homogeneous thinning of the crust can trigger such a gravity-driven convergent flow. Interestingly, metamorphic core complexes in the western United States are alternatively interpreted in terms of convergent gravitational collapse, following or accompanying the heterogeneous extension of a normal crust (e.g., Gans, 1987; Block and Royden, 1990; Wdowinski and Axen, 1992; Kaufman and Royden, 1994), or in terms of divergent gravitational collapse of a thickened crust (e.g., Coney and Harms, 1984; Wernicke et al., 1987; Malavieille, 1993). It is also interesting to note that convergent gravitational collapse is well expressed in lithospheric deformation associated with meteoritic impacts. Indeed, crustal and lithospheric thinning related with meteoritic impacts is followed by a convergent flow of material towards the crater (Melosh, 1982; Melosh

and McKinnon, 1978; McKinnon and Melosh, 1980; Thomas et al., 1997). The flow is responsible for the development of concentric normal faults outside the crater, whereas reverse faults develop at the impact zone.

6. Conditions for gravitational collapse

Divergent gravitational collapse of the continental crust may result from and follow any process that tends to locally increase the thickness of the crust. Subduction zones and continent–continent collisional zones are end-member tectonic environments where thick crust and, therefore, divergent gravitational collapse, can be expected. In subduction zones and continental collision associated with continental mantle subduction, the thick crustal accretionary wedge and the excess in gravitational potential energy are partly supported by shear stresses at the base of the wedge (Davis et al., 1983; Dahlen, 1984; Platt, 1986). In contrast, in the indentation model where a strong continental lithosphere (the indenter) collides with a weak continental lithosphere, basal shear stresses are neglected and the thick crust is supported by compressional stresses, the strength of the thick crust and the strength of the surrounding regions. Initiation of collapse results from changes in the balance of forces that generate and support crustal thickness contrast during convergence (England and Houseman, 1988, 1989). These changes include: (1) reduction of horizontal compressional stresses (e.g., related to a modification of global plate motion); (2) reduction of the basal shear stresses due to strain softening process, or alternatively due to the rollback of the subducting slab (Bott, 1982; Malinverno and Ryan, 1986; Royden, 1993); (3) increase of potential energy (e.g., related to the convective thinning of the lithosphere); (4) reduction in strength of the surrounding regions (e.g., due to lateral conductive heating); and (5) reduction of the strength of the crustal wedge, when mechanically decoupled from the lithosphere mantle (e.g., due to a reduction in strength of the Moho region). England and Houseman (1988, 1989) showed that, using the thin-sheet approximation, a reduction in strength of the elevated region (related to thermal relaxation) is unlikely to trigger collapse, as it leads to increased horizontal contractional strain rates. However, this

conclusion may not be valid if the continental crust is (or becomes) mechanically decoupled from the underlying mantle.

Convergent collapse, as described in a number of studies (Block and Royden, 1990; Buck, 1991; Wdowinski and Axen, 1992; Kaufman and Royden, 1994), requires that the heterogeneously extending upper crust is decoupled from the lower crust. It also requires a regional-scale flow within the lower crust from unextended to extended regions and, therefore, that the lower crust represents a low-viscosity channel. These conditions may be achieved if the temperature at the Moho at the time of extension (or shortly after cessation of extension) is sufficiently high (~ 700 °C, Sonder et al., 1987; Kaufman and Royden, 1994).

7. Modes of flow during gravitational collapse and identification criteria

Like many processes leading to mass transfer, gravitational collapse must resolve a space problem to accommodate the flow of material leaving regions of high potential energy. For both divergent and convergent regimes, several types of gravitational collapse can be envisioned depending on the way lateral contrasts in gravitational potential energy are reduced (Figs. 3, 4). These types can be classified in two fundamental modes called “fixed-boundary collapse” (or mode 1) and “free-boundary collapse” (or mode 2). In mode 1, the reduction of contrast of gravitational potential energy is achieved through a transfer of potential energy from regions of high potential energy towards regions of low potential energy (Figs. 3 and 4). Space is provided by a combination of lowering of the Moho, uplift of the crust’s surface and horizontal shortening of regions of low potential energy. In mode 2, there is no transfer of potential energy from high to low potential regions. Lateral variations in potential energy are reduced due to the displacement of a free boundary under the action of gravitational forces. Space is provided by vertical displacements of the Moho and crust’s surface of the deformed region only, leaving the surrounding lithospheric profile largely unaffected.

The two fundamental modes and their variations described below correspond to various possible pro-

cesses that accommodate the flow of the thickened crust as a function of rheology and boundary conditions. Recognising these types of flow during gravitational collapse places important constraints on the conditions that led to collapse.

7.1. Mode 1, fixed-boundary collapse

The excess of potential energy drives flow of material from the thickened crust to the immediately adjacent regions. Consequently, thinning affects the elevated regions, whereas thickening affects the surrounding crust. Mode 1 contributes, therefore, to the lateral growth of the orogenic domain. Three types can be recognised depending on the partitioning of deformation accommodating gravitational collapse within the crust.

Mode 1a of divergent gravitational collapse has been identified by several generations of earth scientists and described in terms of gravity sliding of upper crustal units away from the zone of thick crust (Steinman, 1907; Gignoux, 1948; van Bemmelen, 1955; Bucher, 1956; Choukroune and Séguret, 1970; Debelmas and Kerckhove, 1973). Extensional detachments are activated within the thicker part of the crust and are connected to thrusts in the forelands (Fig. 3a). The deep crust is progressively exhumed beneath detachment faults, whereas the products of erosion of the topography are collected in basins above the detachments or are transported out of the system. The criteria that point towards mode 1a of gravitational collapse include: (1) continuity between normal faults in elevated regions and thrusts in the forelands, (2) normal faults and denudation in the plateaux synchronous with thrusting and thickening in the forelands, (3) little evidence of ductile deformation in the basement underneath normal faults. Mode 1a can be expected following convective thinning of the thermal boundary layer of the lithosphere at an early stage (before thermal relaxation and thermal softening of the crust), or following the reduction in the basal shear stress associated with subduction zones.

In mode 1b, the low-viscosity lower crust is mechanically decoupled from the overlying upper crust. During collapse, flow takes place in the ductile lower crust only leaving the upper crust largely unaffected (Fig. 3b). Because this process does not

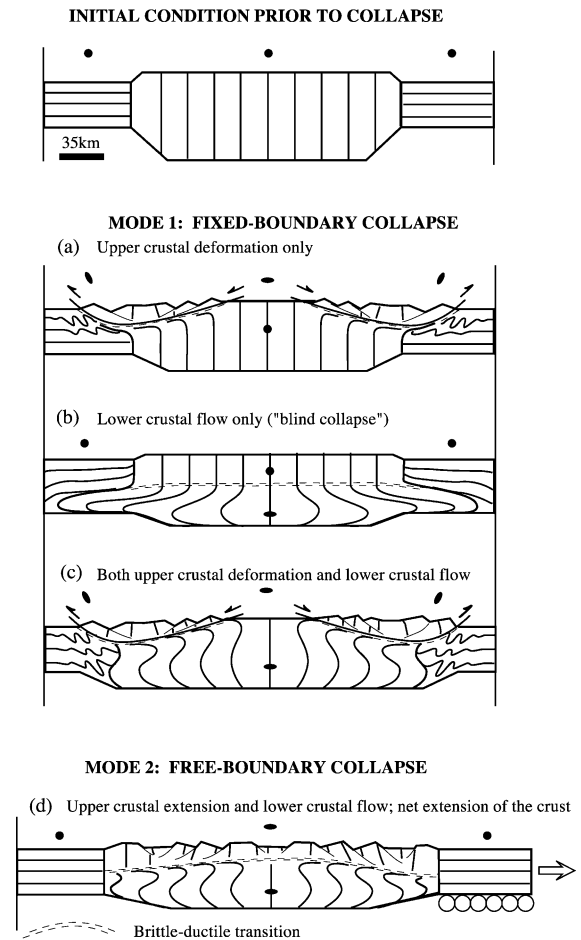


Fig. 3. Illustration of the various types of divergent gravitational collapse affecting a thick continental crust.

leave any structural expression in the upper crust, it can be called “blind collapse”. Horizontal spreading of a low-viscosity region participates in the formation and the widening of the continental plateau at the surface. It leads to the thinning of the orogenic crust and thickening of the crust surrounding the plateau region. Blind collapse may explain the eastward displacement of the eastern topographic front of the Tibetan plateau, which is apparently not accommodated by active structures in the upper crust (like an object creeping under a rug) (Royden, 1996; Royden and Burchfiel, 1995; Royden et al., 1997). The criteria that point towards mode 1b of gravitational collapse include: (1) widening of the plateaux

and thickening of the crust in the forelands without thrusting and (2) reduction of the elevation of the plateaux and crustal thinning in elevated regions without normal faults and denudation. Mode 1b can be expected following mechanical decoupling between a softened thickened crust and the underlying lithospheric mantle.

Mode 1c combines modes 1a and 1b. Material from the upper crust is transferred towards the foreland. The ductile crust flows upward to fill the space beneath the detachment faults and towards the foreland regions which, therefore, undergo thickening. Mode 1c can be achieved when the gravitational force overcomes the contractional strength of the surrounding lithosphere, thus triggering its bulk shortening. The shortening, driven by the excess in potential energy in the elevated regions, creates space to accommodate the collapse of the elevated region (Fig. 3c). The criteria that point towards mode 1c include: (1) continuity between normal faults in elevated regions and thrusts in the forelands; (2) extension and thinning in the plateaux synchronous with thrusting and thickening in the forelands; and (3) strong evidence of extensional ductile deformation in the basement underneath detachment faults (evidence for abundant partial melting, low-pressure high-temperature metamorphism). Mode 1c can be the result of the convective thinning of the thermal boundary layer of the lithosphere following significant thermal relaxation and thermal softening of the crust. Alternatively, mode 1c can be triggered by the softening of the region surrounding the orogenic domain, coupled or not with an increase in gravitational potential energy in the elevated region.

7.2. *Mode 2, free-boundary collapse*

If the gravitational forces stored in the deformed crust can displace the surrounding regions without thickening them, or if a free boundary is adjacent to the orogenic domain (e.g.; an active continental margin), or alternatively, if a phase of tectonic divergence follows the protracted history, then space is provided for the bulk extension of the thickened crust (Fig. 3d). Mode 2 involves the thinning of the entire orogenic domain, accommodated by normal faulting in the brittle upper crust and by ductile flow in the lower

crust. Low-angle detachments and décollements mark the transition between these two crustal layers and there is no flow of material into adjacent regions. Based on the rheological layering of the lithosphere at the time of collapse and the symmetry of extensional deformation, Malavieille (1993) gave a detailed account of the various geometrical models of mode 2 of collapse. Widespread extension occurring at the same time in the whole orogenic domain with no shortening in the foreland should point towards mode 2 of gravitational collapse. The Cenozoic extension in the Basin and Range province could well be very close to the mode 2 of gravitational collapse. Mode 2 may affect thermally softened orogens and may be expected to occur following: (1) changes in the plates motion; (2) rollback and/or retreat of subducting slab; and (3) opening of a back arc basin.

Depending on the interplay between uplift history, evolution of the lithosphere rheology and changes in boundary conditions, it is clear that gravitational collapse very likely evolves in nature from one mode to another through time. Collapse-related structures may, therefore, result from the superimposition of different modes of collapse.

During convergent gravitational collapse of thinned crust, material flows from the surrounding regions towards the stretched crust. Here again, the two modes defined above can be applied (Fig. 4). Mode 1 is a mode of convergent gravitational collapse with fixed boundary, involving a transfer of gravitational potential energy from the surrounding regions towards the stretched domain. Mode 1a involves a transfer in gravitational potential energy through gravity sliding of upper crustal units, a process described along passive margins (Cobbold and Szatmari, 1991). Such a process may involve linked systems of extension and contraction over about 100 km (Peel et al., 1995). Mode 1b involves the flow of the ductile crust towards the thinned domains. This mode is viable during heterogeneous thinning of the crust (e.g., Block and Royden, 1990; Buck, 1991; Wdowinski and Axen, 1992), but remains to be demonstrated in the case of homogeneous thinning. It does not involve horizontal shortening of the stretched domain and it is largely a blind process, as it may have no impact on the upper crust. Mode 1c is a combination of mode 1a and 1b, extensional deformation and thinning affect the sur-

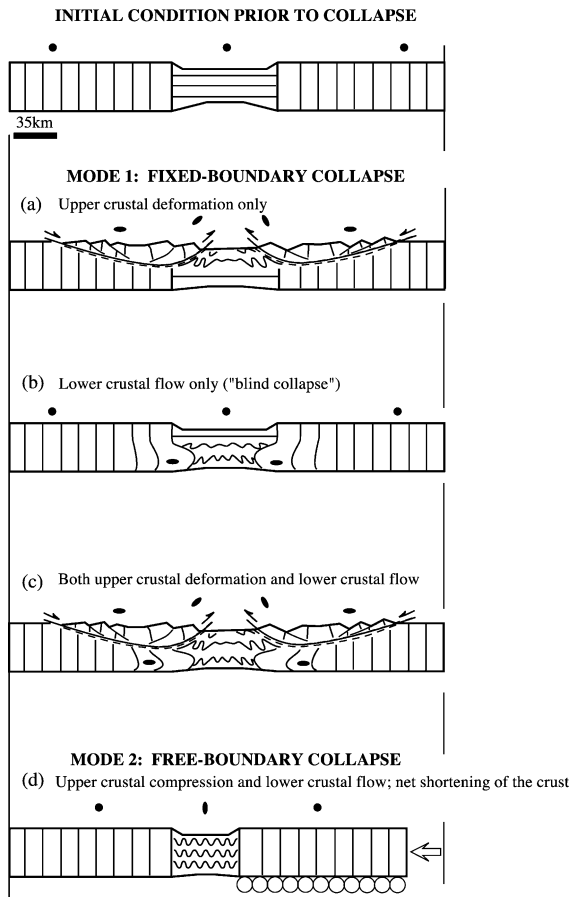


Fig. 4. Illustration of the various types of convergent gravitational collapse that may affect a thinned continental crust.

rounding regions, whereas the thinned crust is shortened. Mode 2 of convergent gravitational collapse (free-boundary collapse) involves no deformation of the surrounding regions, as they are passively dragged by the gravitational force towards the stretched domain.

8. Conclusions

All mass displacements in the Earth, such as erosion, landslide, gravity sliding, gravitational collapse, diapirism, mantle plume, convective thinning of the thermal boundary layer of the lithosphere, sinking of subducted slab, etc., are ultimately the

result of gravitational forces. Gravity-driven displacements can be classified into two categories: Those related to density inversions and those related to lateral density gradients. Gravitational collapse refers to the gravity-driven flow that reduces lateral contrasts in gravitational potential energy. It corresponds to the relaxation of a perturbation in the potential field. Depending on the sign of the perturbation (positive for thickened orogenic crust and negative for stretched crust), two regimes of gravitational collapse can be identified. Divergent collapse corresponds to the relaxation of a positive anomaly, the excess of gravitational potential energy diffuses away from region of high potential energy (i.e., the orogen). Conversely, convergent collapse corresponds to the relaxation of a negative anomaly and involves the flow of material towards the anomaly region. Two modes of gravitational collapse have been defined depending on whether or not transfer of gravitational potential energy occurs from the deformed to the undeformed surrounding regions. Indeed, mode 1 of gravitational collapse is accompanied by deformation of the surrounding regions, whereas in mode 2, motion at the boundaries of the system accommodates gravitational collapse. Variations of these modes can be envisioned depending on the partitioning of deformation in the crust and whether or not the region with an anomaly in gravitational potential energy undergoes finite horizontal extension or shortening. In detail, the deformation of the crust during gravitational collapse is complex. It is controlled by the evolution of its rheology, the mechanical behaviour of the upper mantle, the coupling between the crust and the mantle and of evolution of the boundary conditions.

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