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Gneiss domes and gneiss dome systems

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ABSTRACT

Various mechanisms have been proposed for the dynamic cause and kinematic development of gneiss domes. They include (1) diapiric flow induced by density inversion, (2) buckling under horizontal constriction (i.e., extension perpendicular to compression), (3) coeval orthogonal contraction or superposition of multiple phases of folding in different orientations, (4) instability induced by vertical variation of viscosity, (5) arching of corrugated detachment faults by extension-induced isostatic rebound, and (6) formation of doubly plunging antiforms induced by thrust-duplex development. Despite proliferation of models for gneiss-dome formation, a diagnostic link between the observed geological setting of a gneiss dome and the associated deformational processes remains poorly understood. This is because gneiss domes reflect finite-strain patterns that can be reached through different strain paths or superposition of multiple mechanisms.

To better differentiate the competing mechanisms and to assist the clarity of future discussion, a classification scheme of individual gneiss domes and gneiss-dome systems is proposed. The scheme expands the traditional definition of mantled gneiss domes, which emphasizes the spatial association with synkinematic migmatite and a supracrustal cover, by including those associated with faults. To illustrate possible kinematic interactions between faulting and gneiss-dome development, major geologic properties of two end-member fault-related gneiss domes are discussed: one produced by the development of North American Cordilleran-style extensional detachment faults and the other by passive-roof thrusts in crustal-scale fault-bend folds. Distinguishing the two has become a critical issue in the Himalayan orogen and the western U.S. Cordilleran where emplacement and exhumation of gneiss domes have been variably interpreted to be detachment or thrust related. A systematic examination of gneiss domes related to contractional versus extensional faults indicates that a detachment-related gneiss dome is characterized by the presence of a breakaway system in the footwall, rapid footwall denudation by normal faulting, and coeval development of supradetachment basins in the hanging wall. In contrast, a gneiss dome related to passive-roof faulting is commonly associated with rapid denudation of both hanging-wall and footwall rocks by erosion and the lack of coeval supradetachment basins. The most important aspect of a gneiss-dome system is the spacing between individual domes. The evenly spaced gneiss-dome systems tend to be associated with instabilities induced by density inversion, vertical viscosity variation, or horizontal contraction in a laterally homogenous medium. In contrast, unevenly spaced gneiss-dome systems may be associated with fault development, superposition of multiple folding events, or laterally inhomogeneous properties of rocks comprising the gneiss-dome systems. In nature, gneiss domes are often produced by superposition

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of several dome-forming mechanisms. This has made determination of the dynamic cause of individual domes and dome systems exceedingly challenging.

Keywords: gneiss dome, gneiss dome system, thrust duplex, detachment fault, diapiric flow.

INTRODUCTION

Gneiss domes are important features in orogenic systems (Eskola, 1949; Teyssier and Whitney, 2002), which occur both in contractional (e.g., Burg et al., 1984; Amato et al., 1994; Lee et al., 2000) and extensional settings (e.g., Coney, 1980; Davis, 1988; Lister and Davis, 1989; Harris et al., 2002). Eskola (1949) is perhaps the first person to systematically discuss the geologic setting and characteristics of gneiss domes in major orogenic belts around the world. He defines a mantled gneiss dome to be composed of a metamorphic-plutonic complex in the core that is overlain by supracrustal strata. Eskola (1949) considers that a gneiss-dome core consists of older (prekinematic) granites and coeval (synkinematic) migmatite intruded during gneiss-dome formation. The presence of two generations of granitic rocks in the gneiss domes he examined led Eskola to suggest that the general condition for gneiss-dome formation is the superposition of two orogenic events. The first event is to produce a granitic basement, while the second is to remobilize and to partially melt the older granitic basement, causing vertical inversion of crustal density and upward flow of the metamorphic core. Eskola's proposal that inverted density is the cause for gneiss-dome formation has laid the foundation for later theoretical models (e.g., Fletcher, 1972; Ramberg, 1981). His kinematic model relating production of synkinematic migmatite to the rise of domal structures has been highly influential in the studies of gneiss domes (e.g., Kündig, 1989; Gapais et al., 1992; Amato et al., 1994; Vanderhaeghe and Teyssier, 2001; Teyssier and Whitney, 2002).

Despite the great impact to later research, Eskola's (1949) definition and forming mechanism of gneiss domes should be viewed in the historical context. His synthesis was written before the development of high-precision geochronologic and thermochronologic methods. Consequently, he could not resolve the temporal and therefore causal relationship between migmatization and gneiss-dome formation where clear cross-cutting relationships are lacking. The synthesis was also written before the time when fabric information in ductile shear zones was widely used for reconstructing processes of deep-crustal deformation. As a result, the possible relationship between dome development and its potential effect on structural fabrics of the related ductile shear zones was neglected in Eskola's synthesis.

Since the discovery of extensional detachment faults, many of the classic gneiss domes have been reinterpreted as extensional metamorphic core complexes (Coney, 1980). For example, we now know that the Simplon metamorphic terrane in the Alps, mentioned in Eskola's synthesis (1949) as a type mantled gneiss dome, was related to detachment faulting (Mancktelow and Pavlis, 1994; Wawrzyniec et al., 2001). Similarly, formation of gneiss domes in the Variscan belt discussed by Eskola (1949) has also been attributed to low-angle normal faulting (= detachment faulting; e.g., Mattauer et al., 1988; Burg and Vanderhaeghe, 1993). These examples indicate that gneiss domes defined by Eskola (1949) have many overlapping similarities to extensional metamorphic core complexes. This is particularly true when supracrustal strata are eroded for both types of structures. Because of this, we need to look for other criteria that can be used to distinguish gneiss domes that formed in different structural settings and associated with different geologic processes. In order to achieve this goal, I propose a classification scheme of individual gneiss domes and gneiss-dome systems. This new classification scheme emphasizes broad geologic associations with gneiss-dome structures. The main motivation of the proposed classification is to provide a transparent correlation between individual classes of gneiss domes and the possible geologic processes that have led to their development.

MECHANISMS OF GNEISS-DOME FORMATION

Before presenting the classification, it is useful to review the currently popular views on the dynamic causes and kinematic development of gneiss domes. This is because these models have strong implications for the resulting geometry and kinematic properties of the dome structures produced by different mechanisms.

Dynamic Models

Classic studies on the origin of gneiss domes emphasize the role of Rayleigh-Taylor instability and diapiric flow induced by density inversion in their initiation and final emplacement (e.g., Fletcher, 1972; Ramberg, 1981; Gilbert and Merle, 1987) (Fig. 1A). These early theoretical and experimental studies have provided many insights into mechanical processes of deep crustal deformation. For example, a diapiric flow may explain rapid decompression and associated partial melting commonly observed in orogenic middle crust (e.g., Teyssier and Whitney, 2002). It may also explain radial stretching lineation and top-outward shearing in a gneiss dome (e.g., Gapais et al., 1992).

In addition to the popular diapiric flow model, instability induced by vertical viscosity variation under contraction has also been considered as a possible mechanism in producing gneiss domes and complex fold patterns (Fletcher, 1991, 1995) (Fig. 2). This mechanism does not require density inversion but considers the strain-softening power-law rheology in a stratified mechanical system. Simulated fold patterns derived from this theoretical approach can successfully reproduce the typical domal and

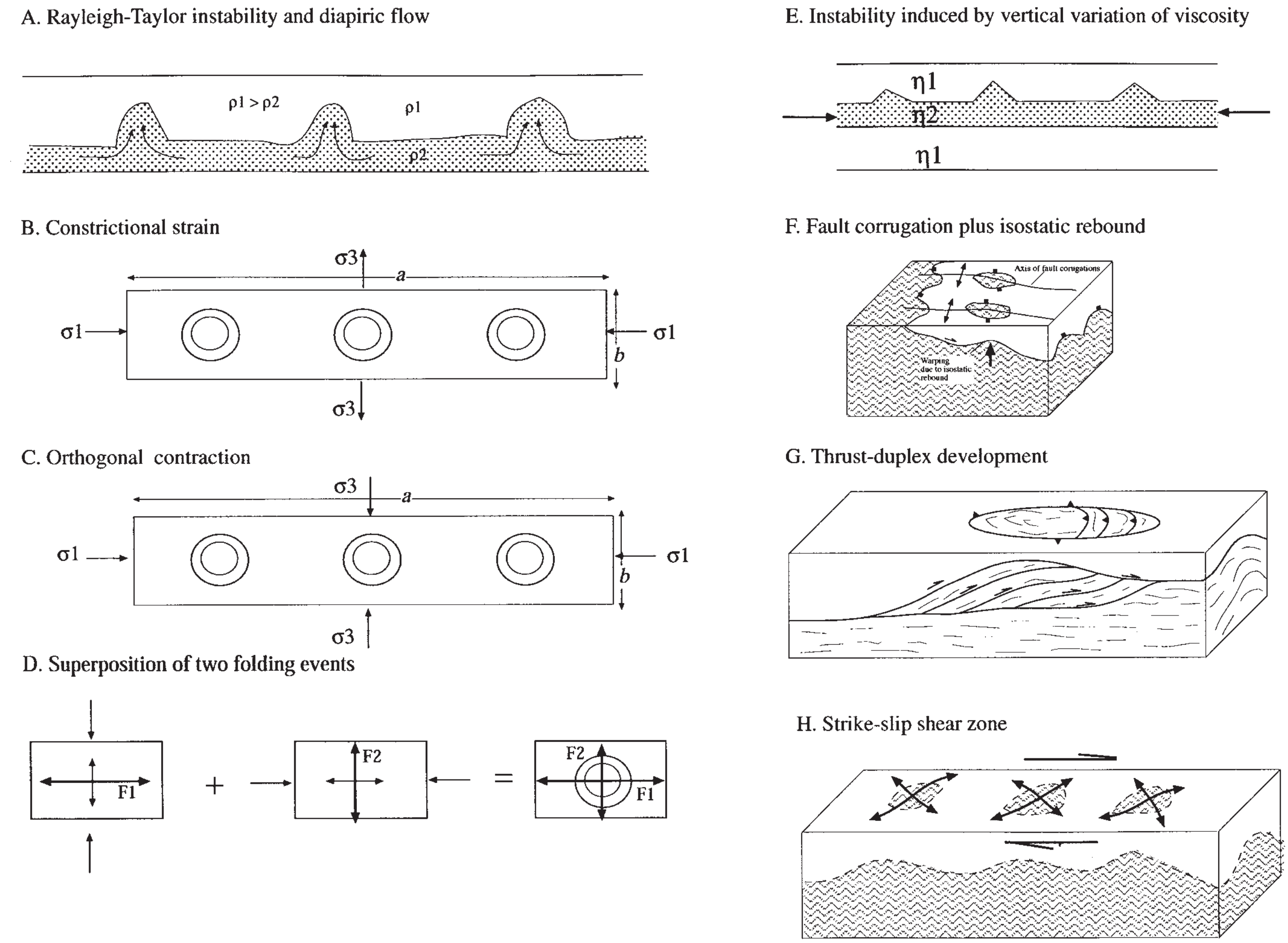


Figure 1. Major geologic processes and mechanical models for the formation of gneiss domes. (A) Rayleigh-Taylor instability and diapric flow; ρ is crustal density. (B) Constrictional strain field under horizontal loads. σ1 and σ 3 are the maximum and minimum principal stresses, and *a* and *b* are the length and width of the extensional belt. Ratio *a/b* defines the aspect ratio of the system. (C) Orthogonal contraction. (D) Superposition of two folding events. (E) Instability induced by vertical variation of viscosity (η). (F) Arching of corrugated detachment fault by isostatic rebound. (G) Development of thrust duplex. (H) Broad folds in strike-slip shear zone.

basinal structures in many orogenic belts and a rich pattern of doubly plunging folds with a wide range of aspect ratios between their long and short axes (Fletcher, 1995).

Transverse compression of upper crust perpendicular to regional extension under horizontal constriction has been used to explain the regularly spaced domal and basinal detachment faults and the associated gneiss domes in the North American Cordillera and elsewhere (Spencer, 1982; Yin, 1991; Yin and Dunn, 1992; Anderson and Barnhard, 1993; Mancktelow and Pavlis, 1994; Fletcher et al., 1995; Diamond and Ingersoll, 2002; Martinez-Martinez et al., 2002; Harris et al., 2002) (Fig. 1C). The major geologic observations supporting this mechanism include (1) folding of syn-detachment-faulting strata concordant with doming, and (2) coeval extension-perpendicular contraction as expressed by folds with axes parallel to the regional extensional direction and the development of conjugate strike-slip faults within extensional belts (Wernicke et al., 1988; Yin, 1991; Diamond and Ingersoll, 2002).

The constrictional mechanism for the formation of gneiss domes is quantitatively evaluated by Yin (1991) using a thin-elastic-plate theory. Yin (1991) suggests that the evenly spaced domes in detachment-fault terranes may be a result of buckling under compression perpendicular to regional extension. This explanation is in dramatic contrast to the diapiric flow model that stresses the role of viscous middle and lower crust in shaping the geometry of gneiss domes and supracrustal strata above. Instead, the elastic buckling model of Yin (1991) emphasizes the importance of strong upper crust in controlling the pattern of middle and lower crustal deformation.

The viscous instability model of Fletcher (1972, 1995) and the elastic buckling model of Yin (1991) are all based on the infinitesimal-strain theory. As a result, these models are best at predicting how the gneiss domes may have initiated, but they are inadequate to describe the growth history of a gneiss dome with finite-strain deformation. Thus, a more complete mechanical description of gneiss-dome evolution requires numerical models that can handle a large magnitude of deformation. An example of such an approach is discussed by Burg and Podladchikov (2000). They simulate how the entire lithosphere could be buckled under horizontal contraction. However, this model is limited to two-dimensional analysis. Therefore, the effect of aspect ratios in controlling the spacing and distribution of gneiss domes cannot be examined. Nevertheless, the process of lithospheric buckling could be important in orogenic development and may lead to the formation of gneiss domes (Teyssier and Whitney, 2002).

Lateral pressure gradient and the resulting extrusion of ductile lower crust have also been cited as a possible mechanism for the formation of gneiss domes. Gilbert and Merle (1987) evaluate the effect of a lateral pressure gradient on the formation of gneiss domes using analogue models. Bird (1991), Avouac and Burov (1996), Royden (1996), and Beaumont et al. (2001) show that extrusion of ductile lower crust in an orogenic system can be driven by a topographically induced pressure gradient. In their thermomechanical model, Beaumont et al. (2001) demonstrate that the location of lower crustal extrusion is controlled by rheological contrast between upper and lower crust and erosion rates at the orogenic front. A high erosion rate and strong upper crust could induce extrusion in the orogenic front, while a low erosion rate and weaker upper crust would lead to extrusion in the internal zone of an orogenic system. Beaumont et al.'s (2001) model links dome formation and partial melting of subducted continental crust with the climatic condition that controls the erosion rate. The model can be tested using thermochronology to determine the exhumation rate in the mountain range and sedimentology of the foreland basin to constrain the erosional history. The limitation of Beaumont et al.'s (2001) model is that it is two-dimensional, that is, the "domes" simulated by the model are in fact cylindrical antiforms.

Kinematic Models

Coeval orthogonal contraction or superposition of two or more folding events could also create gneiss domes (Ramsay, 1967; Steck et al., 1998; Dèzes, 1999; Dèzes et al., 1999; Fowler and Osman, 2001) (Figs. 1C and 1D). Although both processes imply constriction in terms of finite strain in three dimensions, they have distinctive kinematic meanings and tectonic implications.

There are at least three fault-related processes that can produce gneiss domes: (1) thrust-duplex development (e.g., Makovsky et al., 1999) (Fig. 1G), (2) arching of corrugated detachment faults by extension-induced isostatic rebound (Spencer, 1984, 2000; John, 1987; Lister and Davis, 1989) (Fig. 1F), and (3) development of broad folds in strike-slip zones (Pêcher and Le Fort, 1999) (Fig. 1H). In order to develop a domal uplift by a thrust duplex, the cumulative magnitude of shortening absorbed by the duplex system must vary along strike. Such a style of deformation has been documented in the thin-skinned Cordilleran foreland fold-thrust belt (e.g., Fermor and Price, 1987; Yin and Kelty, 1991). These structures may have also developed in the western Himalaya, producing the large thrust windows of the well-known Main Central Thrust (Searle et al., 1992; Gapais et al., 1992; Frank et al., 1995; Fuchs and Linner, 1995; Wiesmayr and Grasemann, 2002).

The process of warping a corrugated detachment fault appears to be similar to superposition of two orthogonal sets of folds. However, the wave-like corrugated fault geometry is a primary structural feature formed during fault nucleation (e.g., John, 1987; Spencer, 2000). Although isostatic rebound warps the detachment fault, the folding process is synchronous with regional extension during the late stage of detachment-fault development (e.g., Spencer, 1984; Lister and Davis, 1989).

CLASSIFICATION OF GNEISS DOMES

Because of diverse possible mechanisms for gneiss-dome formation, it would be desirable to have a classification scheme that can relate the structural setting of a gneiss dome to the associated processes. Such classification may also provide a basis for the clarity of future discussion when comparing gneiss domes of different origins. In the following, I present two classification schemes: one for individual gneiss domes and another for gneiss-dome systems. The classification schemes emphasize the geometric and kinematic relationships between gneiss domes and faults. The latter includes ductile shear zones. The proposed classification also attempts to correlate the geometric patterns of gneiss-dome systems and their geologic settings with the possible dynamic causes. The type examples of gneiss domes and gneiss-dome systems provided below are mostly Cenozoic in age from the North American Cordillera and the Himalayan orogen. The reason to focus on these two regions is fourfold. First, results of integrated geologic investigations are most readily available from the two areas. Second, the plate-tectonic settings at a regional scale and the structural frameworks at a local scale are relatively well understood. Third, the relatively abundant geochronological data make it possible to determine the time scales for the formation of gneiss domes. Fourth, the young ages preclude the untractable superposition of deformational phases that are common for the Precambrian gneiss domes; this allows a direct examination of the fundamental mechanisms and geologic processes that were responsible for gneiss-dome development.

Individual Gneiss Domes

Eskola (1949) defines a mantled gneiss dome as comprising a core of granite, migmatite, and metamorphic rocks that are overlain by layered metasedimentary or metavolcanic strata. A mantled gneiss dome is, therefore, typically expressed by outward dipping of both gneissic foliation in the metamorphic core and layering of its cover sequence (Eskola, 1949).

This definition is somewhat arbitrary, because whether the cover sequence is preserved depends on the magnitude of erosion and thus the exposure level. Due to deep erosion, many geologists working on Precambrian crystalline basement rocks are forced to expand the concept of mantled gneiss domes to include those without cover sequences (e.g., Holm and Lux, 1996; Borradaile and Gauthier, 2003). This problem requires that we relax the original definition of mantled gneiss domes to include all domal structures that are cored by metamorphic rocks and whose geometry is defined by concentric and outward-dipping gneissic foliation, with or without the cover sequence. The outward-dipping geometry of a gneiss dome is defined at the time of dome formation. If the domal structure is later tilted, the tilting must be removed using paleo-horizontal and way-up indicators such as those discussed by Burg and Vanderhaeghe (1993).

Another limitation of the classic concept of mantled gneiss domes is its emphasis on the role of crustal melting. Eskola (1949) was aware of the existence of gneiss domes that are not associated with synkinematic plutons, but he did not elaborate on the characteristics of these gneiss domes nor discuss their kinematic origin. The Kangmar dome in south-central Tibet is a good example of a gneiss dome without the association of synkinematic plutons, at least at its current exposure level (Lee et al., 2000). As shown by Ramsay (1967) and Fletcher (1995), gneiss domes without spatial association of synkinematic plutons could develop by formation of doubly plunging antiforms.

In order to provide a diagnostic link between observations and formational processes, we may divide gneiss domes into (1) *fault-related* and (2) *fault-unrelated gneiss domes* (Fig. 2). This classification is observationally based. That is, the nature

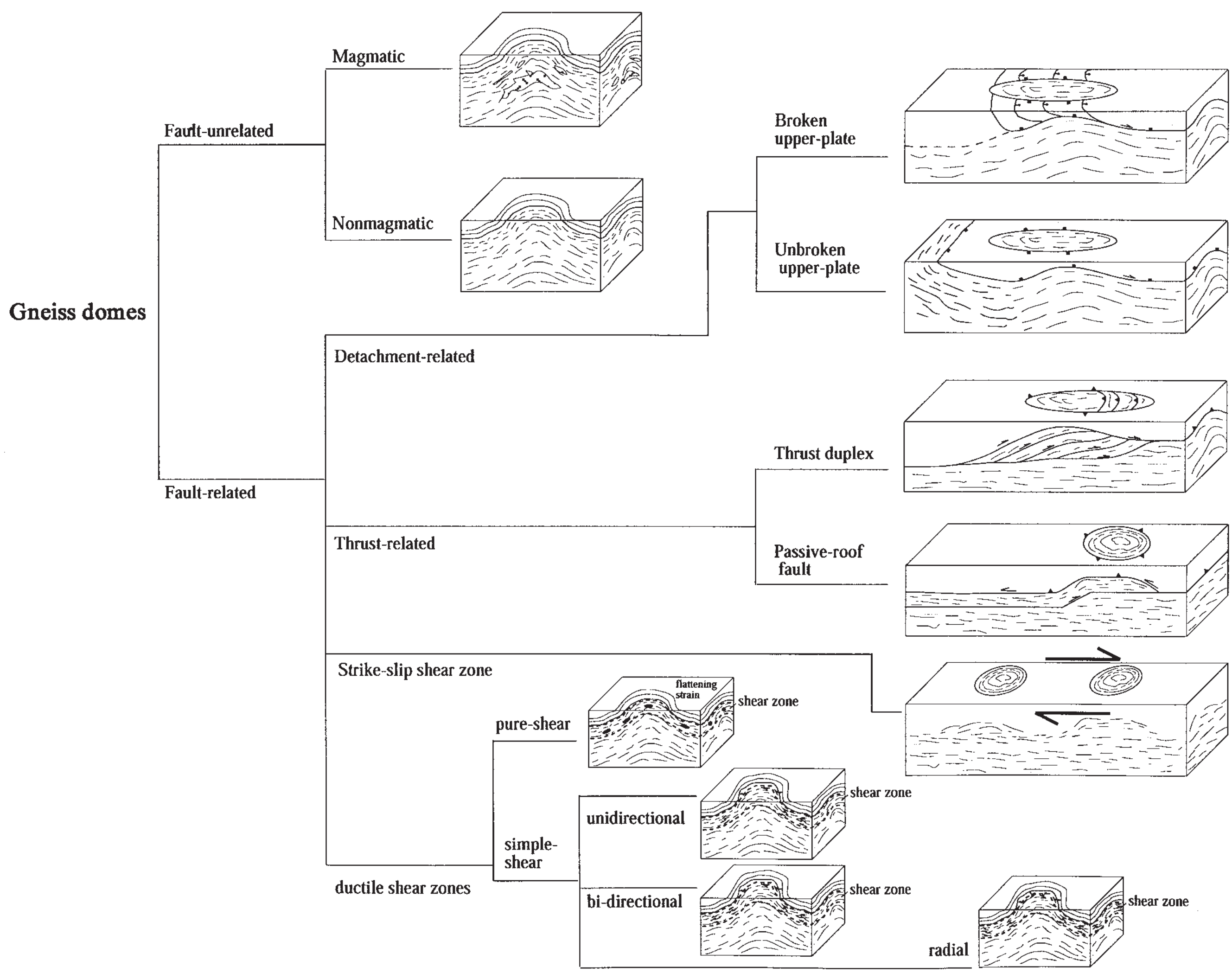


Figure 2. Classification of individual gneiss domes.

of a gneiss dome can be established once its field relationship is adequately documented.

We may further divide the fault-unrelated gneiss domes to *magmatic* and *nonmagmatic gneiss domes*, a scheme implied in the discussion of Eskola (1949) but explicitly proposed by Edwards et al. (2002). This division is important because it provides a critical constraint on the mechanism of gneiss-dome formation. Igneous intrusions in magmatic gneiss domes could either be the cause (Amato et al., 1994; Edwards et al., 2002) or a result of gneiss-dome formation (Teyssier and Whitney, 2002). Nevertheless, both processes emphasize the role of buoyancy in the gneiss-dome development. In contrast, gneiss domes formed without the association of synkinematic intrusions would require the involvement of horizontal contraction and the vertical variation of viscosity and density (Fig. 1). The Thor-Odin dome in the Shuswap metamorphic complex in the southern Canadian Cordillera may be an example of a magmatic gneiss dome that appears to be related to the emplacement of an early Tertiary laccolith (Vanderhaeghe et al., 1999). The Bhazun dome in the Zanskar region of the western Himalaya may be another example of magmatic gneiss domes, with its core comprising synkinematic leucogranites (Kündig, 1989; but see alternative interpretation by Robyr et al., 2002).

The fault-related gneiss domes may be further divided into *detachment-related, thrust-related,* and *strike-slip-related* gneiss domes, depending on whether they are spatially associated with these structures (Fig. 2). Detachment-related gneiss domes are a result of crustal thinning, while thrust-related gneiss domes are a result of crustal thickening. It has been noted that some detachment-fault systems have highly extended hanging walls (e.g., the Whipple Detachment System of Davis [1988]), whereas others do not (Pan and Kidd, 1992; Cogan et al., 1998; Axen et al., 1995). To differentiate these two end-member cases, the detachment-related gneiss domes may be further divided into broken upper-plate and unbroken upper-plate domes (Fig. 2), which may have quite different kinematic histories (Wernicke and Axen, 1988; cf. Davis et al., 1986; Lister and Davis, 1989).

Development of ductile thrusts and ductile thrust duplexes can create large-scale structural highs, exposing middle crustal metamorphic rocks (Dunlap et al., 1995, 1997). Thus, thrust-related gneiss domes may be associated with development of thrust systems, such as *passive-roof thrusts* (Yin, 2002) or *thrust duplexes* (Brown et al., 1986; Makovsky et al., 1999; Ding et al., 2001) (Fig. 2). Gneiss domes could also be developed in broad (tens of km wide) strike-slip shear zones as demonstrated in the Karakoram Mountains of the western Himalayan orogen by Pêcher and Le Fort (1999).

Gneiss domes are commonly associated with ductile shear zones draping over the metamorphic cores. The ductile shear zones could have experienced dominantly pure-shear deformation (e.g., Vanderhaeghe et al., 1999; Lee et al., 2000) or simple-shear deformation (e.g., Kündig, 1989). Hence, we may also group the gneiss domes by the association of the type of ductile shear zones as *pure-shear gneiss domes* and *simple-shear gneiss domes* (Fig. 2). The simple-shear gneiss dome may be further divided in terms of the shear-zone transport direction into (a) *unidirectional*, (b) *bidirectional*, and (3) *radial* gneiss domes (Fig. 2). As discussed below, the unidirectional and bidirectional gneiss domes may result from a regional strain field, whereas the radial-simple-shear gneiss domes may be produced by a local strain field, most likely associated with density inversion leading to diapiric flow.

The classification outlined above demands a more comprehensive understanding of the geological setting within which a gneiss dome is developed. Thus, determining the temporal and spatial relationships to a gneiss dome, igneous intrusions, and major structures (faults, ductile shear zones, and folds) is a prerequisite in defining the nature of the gneiss dome. Also note that the above classification does not provide unique correlation between the types of gneiss domes and the processes leading to their development. For example, a nonmagmatic gneiss dome could either be induced by development of a doubly plunging antiform under orthogonal contraction (e.g., Fletcher, 1995) or under constrictional strain (Yin, 1991; Mancktelow and Pavlis, 1994; Fletcher et al., 1995). Similarly, a magmatic gneiss dome may be produced by extension (Dèzes et al., 1999; Vanderhaeghe et al., 1999) or contraction (Kündig, 1989). Finally, it should also be pointed out that the proposed classification only lists the end-member cases. For example, a magmatic gneiss dome could be associated with fault development. Because deep crustal structures are usually not exposed, a gneiss dome without obvious association with faults on the surface does not preclude its potential tie with faults at depth (e.g., Burg et al., 1984; Makovsky et al., 1999; Lee et al., 2000).

Like fault-related folds (e.g., Suppe, 1983; Boyer and Elliott, 1982), formation of gneiss domes and development of spatially associated faults may not have a cause-and-effect relationship. That is, both structures are an expression of a unified finite-strain field that could be produced by the same regional stress or boundary conditions applied in the far field. Similarly, formation of gneiss domes and emplacement of spatially related migmatite may have no causal relationship. Both geologic features could be the result of heat-generation processes, such as frictional heating or tectonically induced decompression (e.g., England et al., 1992; Harris and Massey, 1994; Harrison et al., 1998).

Gneiss-Dome Systems

Gneiss domes rarely develop as isolated structures. Instead, they commonly occur as a group of structural highs with a variety of sizes and geometric arrangements in map view (e.g., Pêcher and Le Fort, 1999; Lee et al., 2000). The spatial distribution of gneiss domes in turn may be tied to the mechanism of their formation. For example, Rayleigh-Taylor instability (e.g., Ramberg, 1981) and elastic buckling (Yin, 1991) would both predict the occurrence of evenly spaced gneiss domes in a homogenous medium. These models also suggest that the arrangement of the domes in map view may be related to the aspect ratio of the region (i.e., width versus length of an extensional belt) that is under the influence of either Rayleigh-Taylor instability or elastic buckling stress. The possible link between the spatial distribution of domes and their developmental mechanisms suggests that it is important to tie the gneiss-dome classification to the processes of their formation.

In map view, gneiss-dome systems may be divided into (1) *linear-array* and (2) *nonlinear array systems* (Fig. 3). The linear array system may be further divided into *evenly spaced* and *unevenly spaced* systems. Examples of evenly spaced, linear-array gneiss-dome systems include the Lower-Colorado-River-Trough Extensional Corridor of the southwest United States and the Shuswap metamorphic core complex of southeast British Columbia in the Canadian Cordillera. In both places, gneiss domes related to detachment faulting are spaced 40–50 km apart (Yin, 1991; Teyssier and Whitney, 2002). The nonlinear array system may also be divided into evenly spaced and unevenly spaced subclasses. This distinction is critical because buckling, Rayleigh-Taylor instability, and instability induced by vertical viscosity contrast in a laterally homogeneous medium can all produce evenly spaced dome systems. On the other hand, gneiss domes related to fault development (e.g., thrust duplexes) do not have to be evenly spaced. An example of an unevenly spaced, linear-array gneiss-dome system is exposed in the northern Himalayan orogen, where a dozen of gneiss domes with variable sizes and spacing are distributed over a distance of 1500 km along the strike of the Himalayan orogen (Burg et al., 1984; Chen et al., 1990; Hauck et al., 1998; Hodges, 2000; Lee et al., 2000; Murphy et al., 2002). These domes define a large antiform in the northern Himalayan orogen that may have been associated with the presence a large thrust ramp (Hauck et al., 1998) or a thrust-duplex system (Makovsky et al., 1999).

The evenly spaced subclass of nonlinear-array gneiss-dome systems may be further divided into the orthogonal and nonorthogonal subgroups (Fig. 3). Distinction of the two may provide constraints on the mechanical causes of gneiss-dome formation. For example, elastic buckling cannot produce nonorthogonally arranged and evenly spaced domes (Yin, 1991) but the Rayleigh-Taylor instability can (Ramberg, 1981). In addition, the nonorthogonal alignment of gneiss domes may either be explained by superposition of multiple shortening events from different directions or by laterally heterogeneous mechanical properties of the rocks that compose the dome system.

A dozen gneiss domes are exposed in the Karakoram-Nanga Parbat region of the western Himalayan orogen. They are an example of unevenly spaced, nonlinear-array gneiss-dome systems. These domal structures have been associated with Miocene right-lateral transpressional tectonics during eastward extrusion of Tibet (Pêcher and Le Fort, 1999). Several irregularly distributed gneiss domes are also documented in the high-grade Zanskar crystalline complex between the Main Central Thrust below

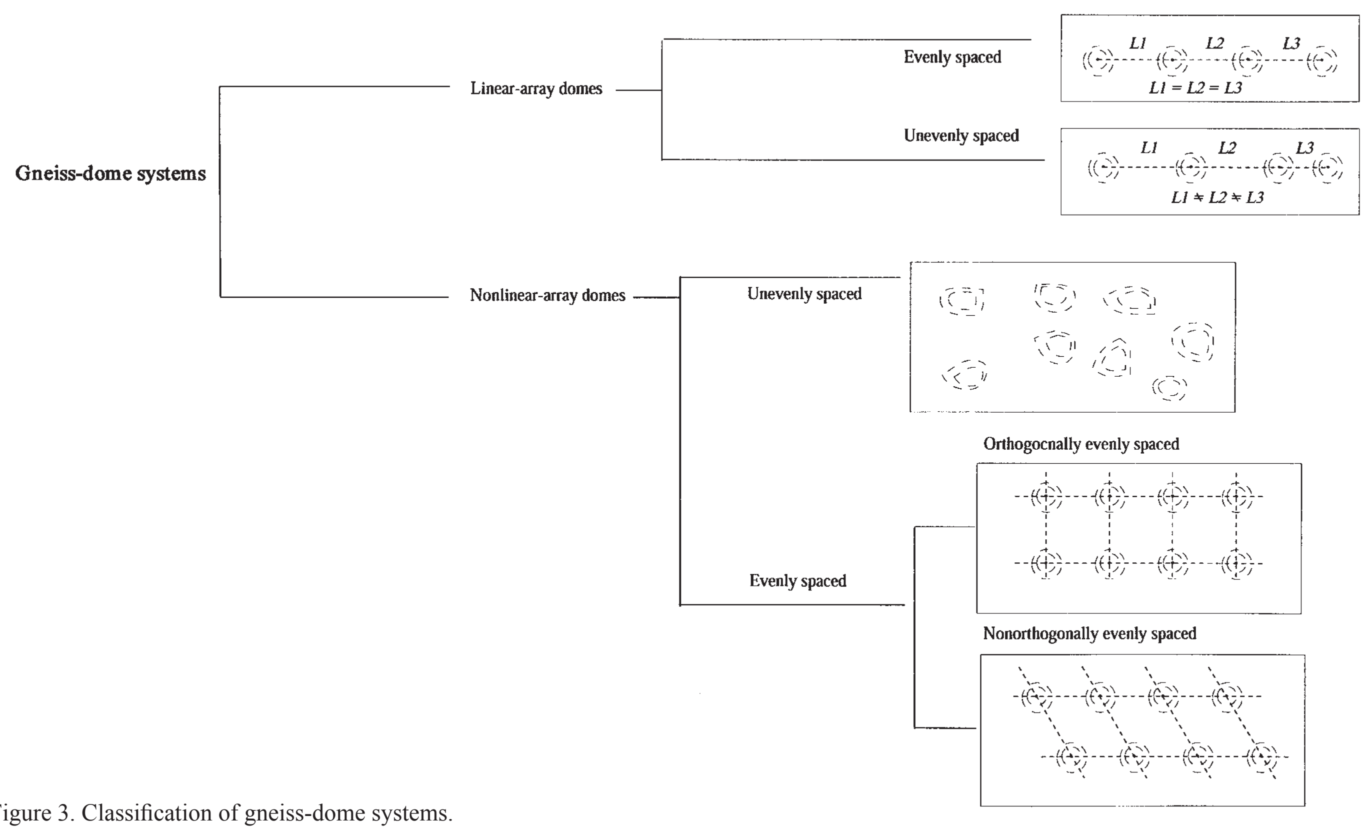


Figure 3. Classification of gneiss-dome systems.

and the South Tibet Detachment (= Zanskar Shear Zone) above (e.g., Kündig, 1989; Walker et al., 2001). Their formation has been attributed to superposition of magmatic injection (Kündig, 1989), Cordilleran-style extension (Dèzes et al., 1999), or polyphase superposition of contraction (Robyr et al., 2002).

PROPERTIES OF MAGMATIC AND FAULT-RELATED GNEISS DOMES

The above classification is purely descriptive. However, relating each type of gneiss dome to the exact mechanism for its formation can be difficult. This is illustrated by the research history of the Miocene Kangmar dome in the northern Himalayan orogen in south-central Tibet, Tertiary domal structures exposing the Pelona-Orocopia schist in southern California, and the Miocene gneiss domes in the Zanskar region of the western Himalaya. The formation of the Kangmar dome was first attributed to thrusting at its base (Burg et al., 1984). In contrast, Chen et al. (1990) later relate its development to Cordilleran-style detachment faulting. More recent studies associate the development of the Kangmar dome to folding of a mid-crustal detachment fault (Hauck et al., 1998), thrust-duplex formation (Makovsky et al., 1999), or large-scale underthrusting (Lee et al., 2000). In southern California, the Pelona-Orocopia schist is exposed in a series of domal structures that are overlain by major folded low-angle faults (Crowell, 1975; Ehlig, 1981). Their exhumation has been attributed to thrusting (Crowell, 1981), extensional detachment faulting (Jacobson et al., 1996), and passive-roof faulting in a crustal-scale fault-bend fold system (Yin, 2002). As mentioned before, the origin of the gneiss domes in the Zanskar region has also been debated and superposition of multiple mechanisms has been proposed (Kündig, 1989; Dèzes et al., 1999; Robyr et al., 2002). In the following, I discuss the geologic properties of three types of gneiss domes: magmatic, detachment-related, and thrust-related. The aim of the discussion is to help focus on observable geologic features that can be used to differentiate gneiss domes formed in different settings and associated with different geologic processes.

Magmatic Gneiss Domes

Despite the fact that the diapiric flow model of Eskola (1949) has been the most popular mechanism for the formation of gneiss dome, there has been little structural evidence to support it. The main predictions of this model are (1) the formation of the gneiss dome is synchronous with plutonic intrusion immediately below the dome, and (2) the stretching lineation trends radially outward with a top-outward sense of shear. The outward flow would allow the cover sequence to be flattened vertically at the center and to slide down outward along the margin of the dome. In the Himalaya, the Sanko dome in the northwestern Zanskar region is the only structure that exhibits a semi-radial pattern of stretching lineation, with a top-outward sense of shear (see Figure 4 of Gapais et al., 1992). I am not aware of any such cases in the Mesozoic and Cenozoic Cordilleran orogen. In contrast, unidirectional (the orientation, not the transport direction) stretching lineation is extremely common in magmatic gneiss domes in both the Himalaya and the North American Cordillera. For example, the Bhazun dome in south-central Zanskar region is a bidirectional simple-shear magmatic gneiss dome (Kündig, 1989), whereas the Thor-Odin dome in the southern Canadian Cordillera is a pure-shear magmatic gneiss dome (Vanderhaeghe et al., 1999). The observation that stretching lineations keep constant orientation in a magmatic gneiss dome has been attributed to the superposition of a strong regional strain field over a weak local strain field (Kündig, 1989; Vanderhaeghe et al., 1999). The latter may be produced by diapiric flow and would produce a radial-simple-shear gneiss dome without the influence of regional strain. The general lack of radial stretching lineation in magmatic gneiss domes in the Himalaya and the North American Cordillera strongly indicates that the finite strain generated by magmatically induced buoyancy must be insignificant when compared to the regional strain field generated by plate tectonics. This conclusion casts serious doubts on the general role of synkinematic magmatism in creating gneiss domes in orogenic systems as originally proposed by Eskola (1949).

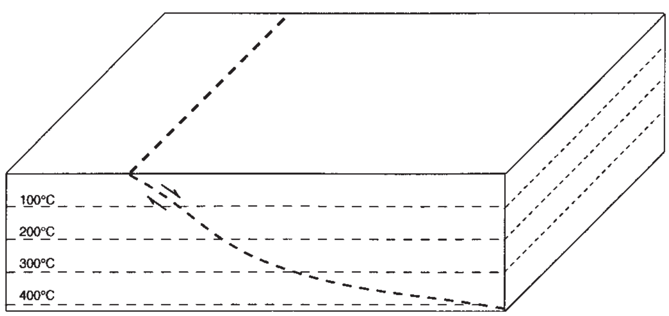
Detachment-Related Gneiss Domes

A typical Cordilleran-style detachment-fault system consists of a brittle detachment fault, a breakaway zone, a highly extended upper plate, a mylonitic shear zone immediately below the detachment fault, and supradetachment basins (Coney, 1980; Lister and Davis, 1989; Friedmann and Burbank, 1995) (Fig. 2). Extension along the detachment fault and its hanging-wall faults causes crustal thinning and resulting isostatic rebound (Spencer, 1984) (Fig. 4A). When superposing on corrugated faults and ductile shear zones the isostatic-rebound process may lead to the formation of gneiss domes in extensional detachment-fault terranes. In both the evolving-shear-zone model of Davis et al. (1986) and the rolling-hinge model of Wernicke and Axen (1988) (also see Axen and Bartley [1997] for an updated review), the master extensional detachment fault soles into a subhorizontal mid-crustal shear zone. As a result, the detachment fault exhibits a listric shape that may be viewed by a first approximation as a flat-ramp geometry. Such a geometry implies that the crustal section above and below the inclined fault ramp is extended and thinned the most and hence should be warped upward the most by isostatic rebound (Spencer, 1984). This observation is important because it means that a detachment-related gneiss dome typically exposes a segment of the footwall ramp, but not its flat (Fig. 4). This in turn requires that an exposed domal detachment-fault window should preserve a truncational relationship between the footwall isograds and the detachment fault (Fig. 4). In addition, the metamorphic grades in the footwall should increase toward the detachment fault across the footwall ramp. In contrast, gneiss domes related to the development of passive-roof faults always exhibit a *decrease* in the footwall metamorphic grades toward the roof fault (see Fig. 5). It is certainly possible that the flat segment of a detachment fault is warped into a dome, perhaps due to buckling under constrictional strain. In this case, the metamorphic grades in the footwall would decrease toward the detachment fault, similar to the distribution of metamorphic grades in the footwall of a passive-roof fault. However, in the latter case a footwall ramp cross-cutting footwall metamorphic isograds must be present.

The detachment fault model also requires the footwall rocks to cool progressively toward the fault. That is, footwall rocks immediately below the detachment fault should have a younger cooling age than those farther away from the fault (Harrison et al., 1995; Stockli et al., 2002). Finally, detachment-related gneiss domes are commonly associated with supradetachment basins immediately adjacent to the gneiss domes in the hanging walls (Friedmann and Burbank, 1995). These basins typically exhibit a growth-strata relationship against either the master detachment faults or their hanging-wall normal faults (e.g., Dorsey and Becker, 1995).

Passive-Roof Fault and Gneiss Domes

The possibility of gneiss-dome development by contraction has been discussed by many workers (Brown et al., 1986; Makovsky et al., 1999; Yin, 2002; Robyr et al., 2002). In parallel to the above discussion on the kinematics of a detachment fault system, the relationship between a major thrust system and prekinematic isograds is shown in Figure 5. Here we only focus on the evolution of a fault-bend fold system because it captures the essence of thrust-duplex development as well. We also neglect the lateral variation of shortening along strike of the duplex, a prerequisite for creating a domal structure by a thrust duplex. But this simplification is not crucial in the following discussion. The fault-bend fold system consists of a basal thrust and a passive-roof fault that has an opposite transport direction to the basal fault. As mentioned above, the distinction between gneiss domes created by a passive-roof thrust and a detachment fault in some cases is not straightforward, as exemplified by the debate on the exhumation history of the Pelona-Orocopia Schist in southern



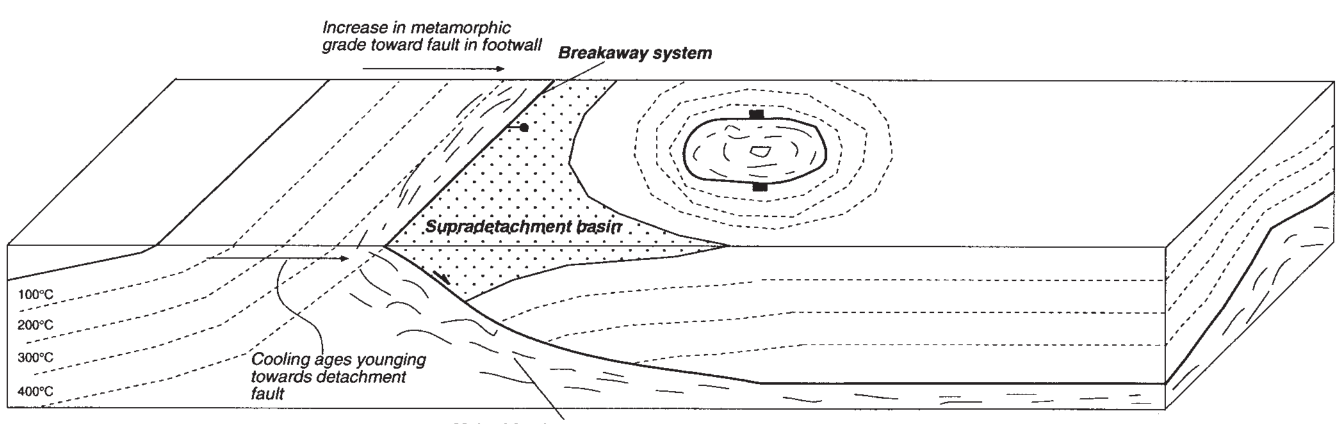


Figure 4. Kinematic development of a gneiss dome related to extensional detachment faulting. The most important geologic features associated with a detachment-related gneiss dome are (1) the presence of supradetachment basins, (2) an increase in footwall metamorphic grades toward the detachment fault, (3) the presence of a breakaway system, and (4) a decrease in footwall cooling ages approaching to the detachment fault.

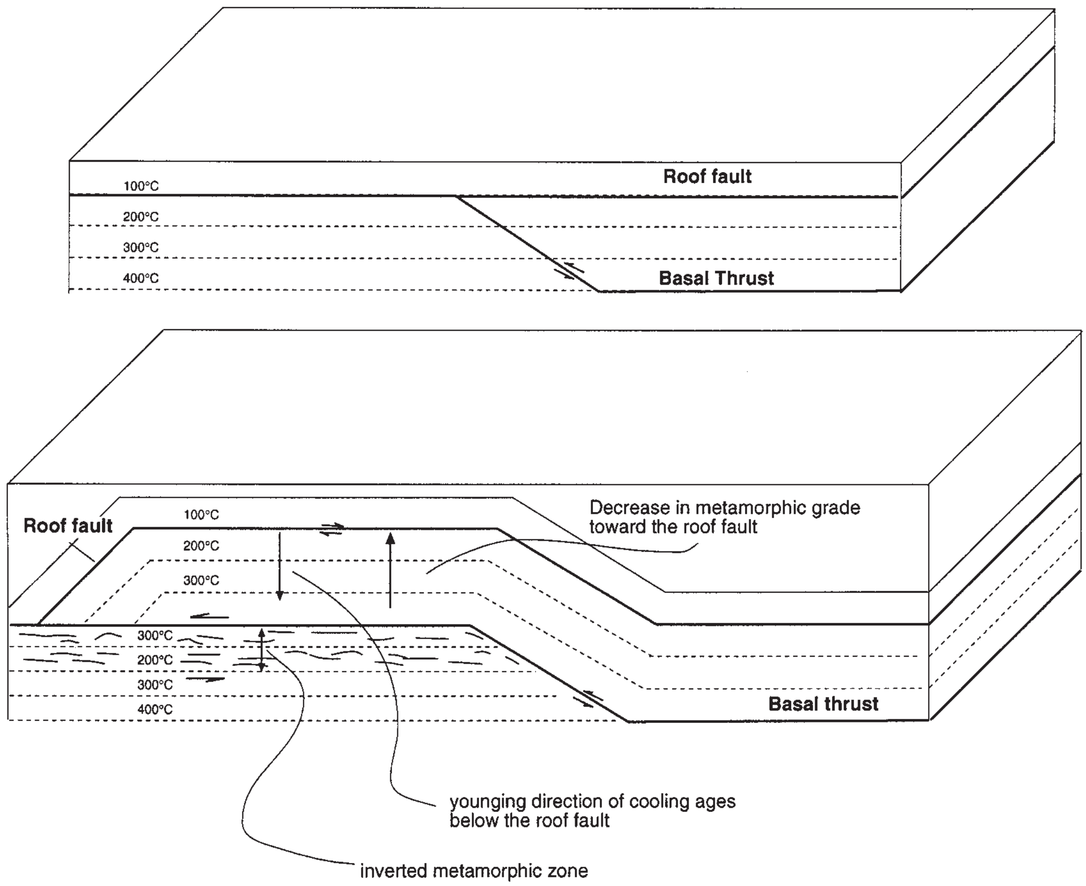


Figure 5. Kinematic history of a gneiss dome associated with a flat-ramp basal thrust and a passive-roof fault with an opposite sense of shear to the basal fault. Note that the metamorphic grades always decrease toward the passive-roof thrust if no strong postmetamorphic deformation modifies the prekinematic isograds. The footwall cooling age becomes younger away from the roof fault.

California (Jacobson et al., 1996; Yin, 2002). Thick-skinned ductile thrusts exhibiting flat-ramp geometry have been documented in the Himalayan orogen (e.g., Johnson et al., 2001). Several workers have successfully constructed balanced cross sections across the Himalaya (Schelling and Arita, 1991; Schelling, 1992; DeCelles et al., 2001). The projected décollement as predicted by the balanced cross sections have been verified by the results of later deep reflection seismology (e.g., Hauck et al., 1998).

The kinematic process shown in Figure 5 is valid only if fault motion does not alter the thermal structure, and thus, the prekinematic isograds are frozen in the thrust sheet as they are transported along the basal thrust. However, this may not be true in nature. As demonstrated by several thermo-kinematic models, movement on major thrusts could constantly change the distribution of temperature in a thrust system (e.g., Shi and Wang, 1987; Ruppel and Hodges, 1994; Harrison et al., 1998). In addition, ductile deformation such as folding and the development of ductile shear zones may deform the prekinematic isograds, and in some extreme cases, may even produce inverted metamorphic isograds along the basal thrust (Searle and Rex, 1989; Hubbard, 1996; Harrison et al., 1998; Vannay and Grasemann, 2001). This latter effect, however, should not affect the distribution of metamorphic grades near a passive-roof fault, although ductile shear along the fault could condense vertically the footwall isograds (Herren, 1987; Dèzes et al., 1999; Vannay and Grasemann, 2001).

The metamorphic grades below a passive-roof fault in a fault-bend-fold system should always decrease upward toward the roof fault. Such a systematic decrease in metamorphic grades in the footwall of the South Tibet Detachment, which is interpreted to be a passive-roof fault (Yin, 2002; cf. Searle, 1999), has been noted along the entire strike of the Himalaya (e.g., Hodges et al., 1996; Le Fort, 1996; Walker et al., 2001; Grujic et al., 2002). This relationship may be used to differentiate detachment-related gneiss domes versus passive-roof-fault–related gneiss domes. The former should have a footwall ramp cutting across metamorphic isograds, whereas the latter only exhibits a flat-over-flat geometry.

Another important property of a gneiss dome induced by passive-roof faulting is that rocks above and below the roof fault experience a similar cooling history resulting from erosion. It is the footwall cooling history and cooling-age pattern that are most useful for differentiating gneiss domes induced by detachment faulting or passive-roof thrusting. In contrast to cooling-age patterns associated with a detachment fault, footwall rocks close to a passive-roof fault cool first whereas the footwall rocks farther away from the roof fault cool later. Because a fault-bend fold occupies a structural high, thrust-induced gneiss domes most likely would not produce coeval sedimentary basins, which is in strong contrast to detachment-fault–related domes that are commonly associated with supra-detachment basins.

DISCUSSION

The classification scheme proposed here emphasizes the role of fault development in gneiss-dome formation. Specifically, debates on whether some prominent gneiss domes in the Himalaya and Southern California are related to extensional detachment faults or thrusts highlight the need for integrated consideration of the geologic setting within which a gneiss dome occurs. For example, the presence of coeval sedimentary basins and their structural settings could be a key to deciphering whether a gneiss dome is associated with detachment faulting or thrusting. Ambiguity for the origin of the Kangmar dome in the Himalaya may be due to the fact that it lies above a flat-over-flat segment of either a thrust or an extensional detachment system. Consequently, examining the deformational and metamorphic history of the dome alone may not provide a unique solution. However, when considering the observation that no coeval supradetachment basins are associated with the dome, the structure most likely originated by contractional deformation.

The geometric arrangement of gneiss-dome systems is a critical indicator of how they developed. In particular, evenly spaced dome systems tend to be associated with instabilities induced by density and viscosity contrast or by horizontal contraction leading to buckling. In contrast, unevenly spaced dome systems are good indicators of their being formed by either fault-related processes, superposition of multiple deformational phases, or lateral inhomogeneous mechanical systems. This correlation between the pattern of gneiss-dome systems and the geologic processes for their development, based on limited case studies, needs to be tested in future investigations.

The correlation that evenly spaced gneiss domes may be related to instabilities induced by vertical variation of density and viscosity is based on the assumption that the mechanical properties of crustal rocks are laterally homogenous. For orogens where lateral variation of mechanical properties of crust is prominent, the gneiss domes may not align evenly spaced, although their initiation was related to the instabilities induced by vertical variation of density and viscosity. In such a situation, differentiation between fault-related and fault-unrelated processes for gneiss-dome genesis may not be straightforward. However, in the Tibetan-Himalayan orogen, major lithologic units and individual accreted terranes appear to be continuous along strike over a distance of 1000 km or longer (Brookfield, 1993; Le Fort, 1996; Hodges, 2000; Yin and Harrison, 2000). This means that lateral heterogeneity and anisotropy should not be the major cause for unevenly spaced domes in the orogen, and thus points to the importance of faults in their formation.

SUMMARY

The classic definition of gneiss domes by Eskola (1949) is incomplete and often leads to confusion. In this paper, the concept of gneiss domes is expanded to all domal structures that are cored by metamorphic rocks, and their geometry is defined by outward-dipping gneissic foliation, after correction of later tilting. Under such a broad definition, we may classify gneiss domes in two fundamentally different classes: fault-related and fault-unrelated. Gneiss domes commonly occur as a group in a large region of an orogenic system. They may be called gneiss-dome systems and can be divided into evenly spaced and unevenly spaced systems. The occurrence of evenly spaced gneiss-dome systems may be associated with instabilities induced by vertical density or viscosity contrast and horizontal load causing buckling. In contrast, unevenly spaced gneiss-dome systems may have been associated with fault development or superposition of multiple deformational phases if the rock property is laterally homogeneous over the gneiss dome system. The most challenging task for geologists is to differentiate gneiss domes related to extensional detachment faults and passive-roof thrusts in fault-bend fold systems. Diagnostic tests between the two are (1) spatial distribution of prekinematic footwall isograds and (2) spatial progression of cooling ages in the footwall rocks. Below a passive-roof thrust isograds typically decrease upward toward the fault while footwall cooling ages become younger away from the fault. In contrast, prekinematic isograds typically increase upward toward a detachment fault while footwall cooling ages decrease toward the fault.

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