PERGAMON

Journal of Structural Geology 23 (2001) 725–731

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Excursus on gravity gliding and gravity spreading

D.D. Schultz-Ela*

Bureau of Economic Geology, The University of Texas at Austin, Austin, TX 78713, USA

Received 10 April 2000; accepted 22 September 2000

Abstract

The terms 'gravity gliding' and 'gravity spreading' have long been used to describe deformation driven by gravity alone. However, the traditional definitions of these terms cannot be applied unambiguously in many situations. The primary difficulties arise because rocks are not ideally rigid, detachment surfaces may not be planar, substrates may be deformable, and rock bodies do not deform in isolation. The term 'gravity spreading' is still useful if it is simply defined as gravity-driven lateral extension and vertical contraction, regardless of basal slope and coherence of the body. I suggest that the term 'gravity gliding' should be used rarely, and only if the defining characteristics are clearly stated and understood. In most cases, more detailed descriptions should be used instead of, or in addition to, either of these terms to capture the behavior of rock masses deforming under gravity.

1. Introduction

Most geologists researching orogenic belts, passive margins, salt tectonics, and glaciology automatically associate certain concepts with the terms 'gravity gliding' and 'gravity spreading', or use them interchangeably (see below). For example, the Gulf of Mexico is widely regarded as a gravity-spreading system, based on the perceptive reasoning of Worrall and Snelson (1989), whereas the Angolan continental margin is thought by many to be a gravity-gliding system (e.g. Mauduit et al., 1997). This kind of pigeonholing can be unproductive or misleading if misconceptions about the meaning of these terms become uncritically built into our attempts to understand certain regions. For the terms 'gravity gliding' and 'gravity spreading' to be useful, they must define identifiable processes, and their distinction must be helpful for discussing gravity-driven deformation. I have frequently found it difficult, however, to unambiguously characterize deformation in numerical and physical models using these terms. This nagging difficulty prompted a re-examination of the concepts of gravity gliding and gravity spreading. I will first briefly review previous usage, then proceed from simple systems, in which the distinction between these two types of deformation is clear, to more complex systems that defy simple characterization. In the process, the major responses of rock to gravity deformation will be reviewed with special emphasis on aspects of salt tectonics, which complicates the classical concepts of spreading and gliding.

2. Traditional definitions

Rock deformation is largely driven by gravity, whether directly or indirectly. Of interest here is dominantly lateral rock movement directly resulting in loss of potential gravitational energy by the system. Such movement has long been categorized by the terms gravity gliding and gravity spreading. The terms have been defined as follows (De Jong and Scholten, 1973a; Jackson and Talbot, 1991). Gravity gliding is generally downslope movement of a rock mass above a weak detachment surface or zone, although part of the rock mass may move upslope if the entire system loses gravitational energy by sliding. Gravity spreading moves material across or up a sloping detachment by vertical flattening of an internally deforming mass.

Gravity gliding (or sliding) requires a dipping basal sliding surface to lower the body's center of gravity. Gravity gliding has been commonly invoked to explain long translations of relatively thin nappes, overthrusts, and klippe (e.g. Smoluchowski, 1909; Bull, 1950; de Sitter, 1954; Maxwell, 1959; Campana, 1963; Heezen and Drake, 1963; North, 1964; Carlisle, 1965; Van Bemmelen, 1966; Pierce, 1966; Temple, 1968; Kay, 1969; Lemoine, 1973 and many other papers in De Jong and Scholten, 1973b; Graham, 1981), particularly prior to widespread acceptance of plate tectonics. Folding, faulting, and chaotic mixing commonly deformed these masses internally, but did not affect the

* Fax: +1-512-471-0140.
E-mail address: schultzelad@mail.utexas.edu (D.D. Schultz-Ela).

0191-8141/01/$ - see front matter
PII: S0191-8141(01)00004-9

underlying strata ('thin-skinned'). In fact, Hsü (1969) contended that gravity sliding only applied to cohesionless (broken) masses, as exemplified by the Heart Mountain thrust, whose upper block he interpreted to be shattered. Other authors distinguished between rigid-block and deformable-block gliding (Voight, 1973), or even more subclasses similarly based on coherency or correlatibility (North, 1964). Later authors tended to apply gravity gliding to rigid, or at least coherent, masses, in which internal deformation is essentially restricted to accommodating motion over an irregular detachment (e.g. Buetner, 1972; Todd, 1983; Mandl, 1988). The detachment may be a thick ductile layer, such as the system of coherent blocks sliding downslope on salt toward the free surface of the Colorado River canyon in Canyonlands National Park, Utah (McGill and Stromquist, 1979).

Thus, gravity gliding deformation is mostly by translation rather than by strain in the rock body. Gravity gliding commonly includes an extensional breakaway zone at the head of a rock mass and a contractional zone at the toe (e.g. Kehle, 1970; Ramberg, 1981; Mandl, 1988; Price and Cosgrove, 1990; Cobbold et al., 1995), but these are not required depending on the surroundings and detachment profile. To qualify as gliding, the allowable size of the distorting head and toe zones relative to that of the block seems to implicitly depend on whether emphasis is on downslope movement or distortion of the mass. Gravity gliding is initially limited by the shear strength of the basal detachment relative to the body's shear stress parallel to the slope, and any impediment to movement at the toe of the block. Higher basal friction or yield strength requires a steeper slope to initiate gliding. The toe of the gliding mass may move upslope (e.g. De Jong and Scholten, 1973a; Turner, 1996), but such climb requires substantially increased downward slope beneath the rest of the mass (Raleigh and Griggs, 1963). The only shared characteristic of all the gravity gliding usages is the inferred dominant downslope translation of rocks, and the general implication of tectonic erosion, thinning, or breakaway at the rear of the gliding mass (e.g. Jackson and Hobday, 1980; Cooper, 1981; Mandl, 1988; Turner, 1996).

Gravity spreading has been applied to gravity-driven internal distortion of a rock mass. If a body's overall center of gravity drops, it may move up a basal slope (e.g. Bucher, 1956; Van Bemmelen, 1960; Price, 1973; Root, 1973; Cooper, 1981; Ramberg, 1981; Janecke, 1992) or downslope (Talbot, 1993; Buetner and Craven, 1996). Movement up a basal slope requires a top surface that slopes in the spreading direction and a means for maintaining that slope if deformation is to continue. At least part of the top surface can subside independently of the basal slope or roughness if the body can expand laterally. Classic model examples of gravity spreading are the vertical collapse and lateral expansion of an initial mound of molasses or silicone putty. Gravity spreading is resisted by the strength of the material. For spreading to begin, the differential stress that gravity induces in the body must exceed any yield strength in the rock. The spreading wedge has been mechanically idealized as a time-dependent viscous fluid having no or low shear strength (Ramberg, 1981; Platt, 1986), a wedge at plastic or frictional-plastic failure above a weak base (Elliot, 1976; Chapple, 1978; Davis et al., 1983; Siddans, 1984; Mandl, 1988; Dahlen, 1990; Martinod et al., 2000), or a wedge weakened and uplifted by a welt at the rear spreading on a weak decollement (Smith, 1981). During deformation, spreading dissipates the released kinetic energy through viscous dissipation, friction, or other processes such as diffusion-controlled creep or pressure solution. The common characteristic of these usages is the pervasive internal deformation as vertical contraction (thinning) drives horizontal extension (stretching).

Gravity gliding and gravity spreading are generally conceptualized by simple systems such as those in Ramberg (1980, 1981) (Fig. 1). Gravity gliding characterizes a block sliding down a slope. Gravity spreading characterizes a mass collapsing vertically and extending laterally. Both processes are driven by a loss of gravitational potential energy as the center of gravity of the deforming body drops in elevation. Most simple diagrams of these processes isolate the deforming bodies from their surroundings. I will discuss those examples, but also more complete systems. To address the heart of the matter, here I restrict our discussion to deformation driven directly by gravity. Although the wedge of a fold-and-thrust belt spreads under gravity, tectonic push from the rear counteracts that by causing horizontal shortening and vertical thickening.

For discussion, gravity gliding and spreading seem to be generally distinguished by two characteristics: whether the body internally distorts during movement, and whether the basal slope is downhill or uphill in the direction of movement. Therefore, gravity spreading can be provisionally characterized as gravity-driven distortion of a rock mass above a basal slope that is horizontal or uphill in the

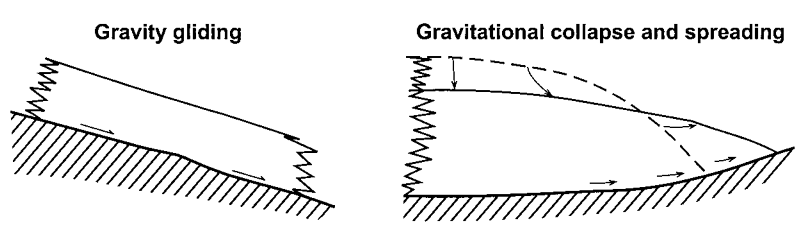

Fig. 1. Simple systems illustrating the generally accepted concepts of gravity gliding and gravity spreading (after Ramberg, 1980, 1981).

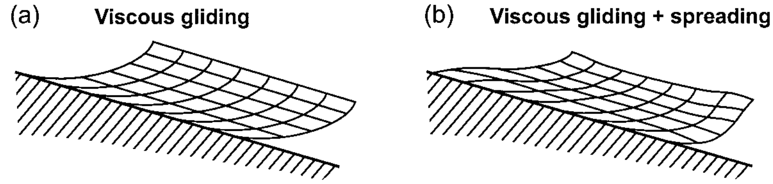

Fig. 2. Behavior of viscous bodies gliding down a slope. (a) Viscous gliding as envisioned by Kehle (1970). (b) More realistic combination of gliding and spreading by collapse and extension.

direction of spreading. Gravity gliding is dominantly rigid downslope movement of a rock mass.

Applying the preceding concepts of gravity gliding and gravity spreading to more general and realistic geological situations requires consideration of several factors, namely: (1) rheology of the body, (2) shape of the detachment, (3) deformable substrate, and (4) deformation surrounding the block. Each of these factors will be discussed in detail below. I generally discuss the two-dimensional (plane strain) simplification here. Extrapolation of the ideas to three dimensions is straightforward.

3. Rheology of the body

According to the working definitions presented here, gravity gliding requires a relatively rigid block to distinguish it from the pervasive strain of a collapsing block in gravity spreading. Gliding of a viscous block has been proposed (Fig. 2a; Kehle, 1970). But as Brun and Merle (1985) note, a viscous block gliding down a slope would concurrently collapse and spread under its own weight (Fig. 2b). Therefore, pure viscous gliding is impossible, and downslope movement of a viscous mass would be a combination of gravity gliding and spreading. By the same reasoning, pure gravity spreading requires a horizontal or uphill basal slope in the direction of spreading. Otherwise, a component of gravity gliding may be present. If gravity gliding is restricted to glide above a thin detachment, then a block that moves downslope by shape change above a stuck base would be properly classed as gravity spreading rather than gliding. Under this restriction, 'viscous gliding' (Kehle, 1970) is actually gravity spreading. Therefore, the distinction between gravity gliding and spreading may depend on two factors: (1) whether the block strains, and (2) whether basal shear occurs across an arbitrarily-defined 'thin' detachment. The problem of defining the basal detachment will be further discussed in the section on a deformable substrate.

A spreading block may strain by several processes. The strain need not be penetrative in the body, but it must cause the entire block to change shape. Few rock bodies actually flow viscously in the shallow crust, so the strain could be due to processes such as distributed faulting, movement across deformation bands or shear zones, or pressure solution. If the strain is by faulting, at some scale it will make more sense to consider the rock mass as individual fault blocks rather than a coherent mass. This problem of scale will be addressed in the section on deformation surrounding a block.

No block of rock is truly rigid—sufficiently high differential stress will inevitably cause failure. A definition of gravity gliding that requires rigidity of the block will tend to be limited to smaller-scale gravity-driven processes. Larger bodies tend to be proportionally weaker than small ones because of the greater possibility of including fractures and inhomogeneities (e.g. Pusch, 1995; Schultz, 1996). Thus, coherent blocks a meter in size are common, but undistorted blocks many kilometers in size are unusual. Preservation of large coherent blocks is favored by a high cohesion, high friction coefficient, low differential stress before downslope restraint is removed, low density, no strain weakening or a high strain threshold for it, and high yield stress or friction coefficient on the basal detachment.

4. Shape of the detachment

The basic concept of gravity gliding assumes a rigid block translating down a constant slope. Gravity cannot move a rock mass up a constant slope unless it distorts, and downslope movement of a distorting mass implies a component of gravity spreading. Curved detachments further muddy the distinction between gravity gliding and spreading. Fig. 3 shows a series of configurations for the gliding block and its underlying detachment surface. Fig. 3a, which has a planar detachment, is clearly gravity gliding. Fig. 3b shows rigid rotation above a curved detachment,

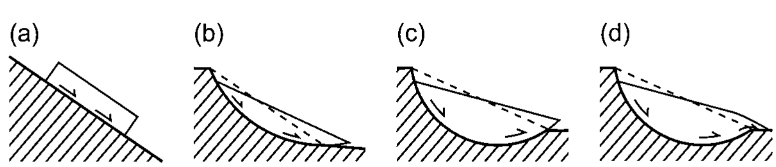

Fig. 3. A block gliding down detachments having various curvatures. (a) Planar detachment. (b) Curved detachment sloping entirely downhill. (c) Curved detachment sloping uphill near base. (d) Likely distortion of block moving on detachment of (c).

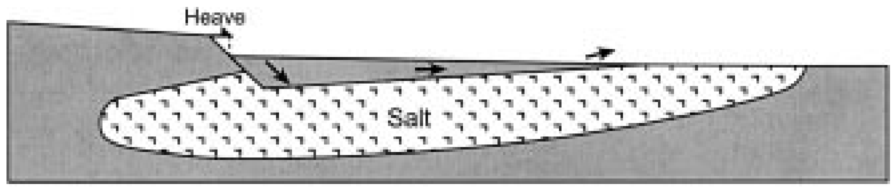

Fig. 4. Block subsiding and translating by gravity into a deformable substrate such as salt. Full arrows indicate movement directions at different locations in roof block.

but the motion still fits the general concept of gravity gliding. This type of curved fault commonly appears beneath slumps. A similar curved detachment in Fig. 3c raises problems with the definition of gliding. Although the block loses gravity potential by rigid motion, it moves up a basal slope at its toe. As shown here, a block can glide under gravity up a curved fault if the surface on the block initially slopes downward in the direction of motion. If Fig. 3c is termed gravity gliding because of its similarity with Fig. 3b, that removes the distinguishing characteristic of only gravity spreading being able to move up a basal slope. The remaining common characteristics in Fig. 3 (a through c) are that the blocks are rigid and the detachment must emerge at a higher point upslope than downslope for gliding by rigid translation or rotation to be possible.

If the ground surface was initially smooth, rigid rotation above a curved fault will create an overhang at the uplifted toe of the rotated block (Fig. 3b and c). Such an overhang of any appreciable size would likely collapse and create the more realistic configuration shown in Fig. 3d. That distortion further blurs the distinction between gliding and spreading. Although the block initially moves rigidly, parts of it collapse under its own weight. Similarly, if the underlying detachment is neither planar nor circular, the block must distort as it slides.

Given the problems of distinguishing between gliding and spreading on the basis of detachment shape, it seems more meaningful and distinctive (at this point) to define gravity gliding only as movement along a detachment of undistorted blocks directly driven by gravity.

5. Deformable substrate

Addition of a deformable substrate, such as salt, creates more difficulty for unambiguously distinguishing between gravity gliding and spreading. A rigid block may simply subside into salt, but more commonly it translates laterally at the same time (Fig. 4, where arrows show motion of roof block). If a fault bounding the block has a dip other than vertical, the fault heave is the lateral translation. As shown by Fig. 4, the base of the block may slope entirely upward in the direction of motion, but the block may still translate under gravity as a relatively rigid block. This type of behavior appears in the roofs of smaller salt sheets (e.g. Wu et al., 1990, Diegel et al., 1995). If gravity gliding is simply defined as rigid motion of the block, the situation in Fig. 4 must be gravity gliding even though the process could be characterized as vertical collapse and lateral extension. The orientation of the base of the block is not useful for distinguishing gliding from spreading above a deformable substrate. The roof of the salt sheet can be described as either gliding or spreading depending on whether the rigid movement or the vertical collapse and lateral extension is emphasized.

Again, the remaining useful characteristic of gliding is that the block remains undistorted during movement. But, the roof block above larger salt sheets rarely remains coherent and rigid (e.g. see figures in Diegel et al., 1995; Schuster, 1995; Mann and Schultz-Ela, 1997). Instead, the roof commonly segments into individual, largely undistorted blocks separated by extensional zones. The front of the block may contract laterally. Therefore, the entire roof is not deforming by gravity gliding, even though some parts of it may be. The following section addresses this problem of the relation of the blocks to their surroundings.

6. Deformation surrounding the block

Most of the preceding discussion focuses on deformation of a single block. Similarly, most diagrams that illustrate gravity gliding show only a single block (note how relations

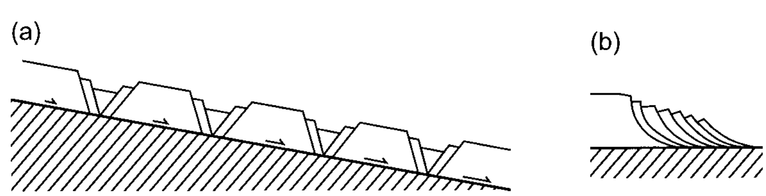

Fig. 5. Gravity deformation of multiple blocks. (a) Individual blocks are gravity gliding, but on a larger scale the system is thinning and extending by gravity spreading. (b) Gravity spreading commonly consists of numerous smaller-scale blocks deforming by gravity gliding.

with the surroundings are ignored in Fig. 1). Salt tectonics invariably considers more comprehensive systems—at least of salt and some surrounding rock. Thus, a definition of gliding versus spreading that relies on individual bodies will have very limited applicability. Fig. 5a illustrates the crux of this problem. A series of blocks are gliding downslope on a thin detachment. Considered in isolation, each of these blocks is clearly gravity gliding. However, they are also progressively separating from each other. When considered as a bulk system, then the blocks are spreading laterally and thinning vertically. From that viewpoint, the system has a component of gravity spreading. Hence the confusion of terms where Voight (1973) describes a system of separating and diverging blocks above a nearly horizontal base as block gliding, whereas Buetner and Craven (1996) describe the analogous Heart Mountain system as gravity spreading. Both authors use both terms in their papers, generally depending on whether movement of a single undistorted block or the whole system is considered. Thus, the scale of the deformation is essential to defining gliding versus spreading. A bulk behavior of gravity spreading will commonly consist of many individual gravity-gliding blocks, particularly if the bulk spreading is by faulting rather than penetrative flow (e.g. Fig. 5b). Indeed, it is difficult to conceive of gravity gliding of a single block in isolation, outside of the geomorphologic realm of individual boulders and slabs. Therefore, any block undergoing gravity gliding will invariably be part of a larger system of gravity spreading. Conversely, on some scale many gravity spreading systems can be viewed as an amalgam of gravity-gliding blocks.

Physical models simulating raft tectonics by Mauduit et al. (1997) further illustrate the problem of distinguishing gliding from spreading in systems of multiple fault blocks. Their models had a horizontal basal slope and a thin salt layer, above which the overburden was deformed by block faulting. Slip on the faults caused overall vertical thinning and horizontal extension: apparently a case of gravity spreading accommodated by movement of many blocks. However, even though the top and base of the salt were horizontal, Mauduit et al. (1997) considered this to be gravity gliding because similar structures developed for basal slopes of 1 and 2°, and in those models the blocks glided downslope. The deformation patterns show progressive changes at steeper basal angles, but there is no clear distinction between gliding and spreading effects as traditionally defined.

Focusing on the behavior of a single block may not be particularly useful. Above the scale of tens of meters, individual blocks that move and stay truly rigid are extremely rare. Some component of bending, extension, or contraction is nearly always present. Therefore, it may be difficult, or even impossible to unambiguously identify zones of pure gravity gliding. Moreover, it is not obvious how to relax the definition of gravity gliding to be more inclusive and useful.

7. More comprehensive classifications

Geomorphologists also study movement of surface material. A brief perusal of a geomorphology text (Chorley et al., 1984) shows several approaches to classifying gravity-driven mass movement. One classification is based on direction of movement (vertical, lateral, or downslope), presence of a transporting agent (mud, water, ice), and coherence of the flow. Another classification proposes a ternary diagram having slide, flow, and heave at its apices. These classification schemes are useful because they systematize many common terms, such as rock fall, soil creep, landslide, etc. Gravity-driven movements in salt tectonics do not have similar descriptive terms, and they add the complication of a thick ductile substrate and a larger scale. The larger scale reduces the likelihood that a block will remain undistorted during deformation. A more comprehensive terminology might be more useful than trying to assign gravity-driven tectonic movements to only two pigeonholes represented by the ambiguously defined concepts of gliding and spreading. An approach based on typical fault patterns found in salt tectonics appears in Rowan et al. (1999). Although based on non-generic descriptions, that classification tends to separate families of faults and surrounding rock into systems with different characteristic behaviors and histories.

8. Summary

The concepts of gravity gliding and gravity spreading are typically defined by the general rigidity of the mass and the orientation of an underlying detachment. The examples discussed here demonstrate difficulties in using detachment configuration as a defining characteristic. Lack of strain in a moving block seems to be the most objective characteristic of gravity gliding. Whether a block is rigid depends on the scale of observation and the amount of strain allowed. On some scale, most gravity-spreading systems that include brittle rocks contain gravity-gliding blocks. Trying to identify zones of rigidity merely for the sake of identifying gravity gliding does not explain much about the dynamics of the overall system. Other examples can be cited that demonstrate difficulties in classifying systems in terms of gliding and spreading.

The term 'gravity spreading' is the most defensible and useful of the two, if it is simply defined as gravity-driven lateral extension and vertical contraction, regardless of basal slope and coherence of the body. I suggest that the term 'gravity gliding' is rarely useful by itself. It should be used sparingly, and only if it is clearly defined when used. If the defining characteristics are not explicitly stated and understood, the term may be burdened with its ambiguities, contradictions, and implications accumulated over many years. In most cases, more detailed descriptions should be used in addition to, or instead of, either of these terms to capture the behavior of rock masses deforming under gravity.

The terms gravity gliding and gravity spreading seem to be most useful for describing the initial tendency of a system to deform: whether the dominant response to gravity appears to be downslope gliding or vertical thinning and lateral extension. But because the two responses are generally not unambiguously separable or distinguishable, the terms should be used in a qualitative, not quantitative, sense.

Acknowledgements

Many thanks to Martin Jackson for discussions and to him, Mark Rowan, Jon Mosar and Jim Evans for thorough reviews of this paper. This material is based on work supported by the Texas Advanced Research Program under Grant No. 003658-0035-1997 and by the members of the Applied Geodynamics Laboratory Consortium, namely, Agip Petroleum, Amoco Production, Anadarko Petroleum, BHP Petroleum (Americas), BP International, Chevron Petroleum Technology, Conoco, Exxon Production Research, Louisiana Land and Exploration, Marathon Oil, PanCanadian Petroleum, Petroleo Brasileiro, Phillips Petroleum, Saga Petroleum, Shell Oil, Statoil, Texaco Exploration and Production, Total Minatome, and Vastar Resources. This paper is published with permission of the Director, Bureau of Economic Geology, The University of Texas at Austin.

References

Buetner, E.C., 1972. Reverse gravitative movement on earlier overthrusts, Lemhi Range, Idaho. Geological Society of America Bulletin 83, 839–846.

Buetner, E.C., Craven, A.E., 1996. Volcanic fluidization and the Heart Mountain detachment, Wyoming. Geology 24, 595–598.

Brun, J.-P., Merle, O., 1985. Strain patterns in models of spreading–gliding nappes. Tectonics 4, 705–719.

Bucher, W.H., 1956. Role of gravity in orogenesis. Geological Society of America Bulletin 88, 1667–1677.

Bull, A.J., 1950. Gravitational sliding. Proceedings of the Geologists' Association 61, 198–201.

Campana, B., 1963. The emplacement of Prealpine and Helvetic nappes as submarine gliding of plastic masses. In: Carey, S.W. (Ed.). Syntaphral Tectonics and Diagenesis—A Symposium. University of Tasmania, Hobart, Tasmania, pp. E1–E6.

Carlisle, D., 1965. Sliding friction and overthrust faulting. Journal of Geology 73, 271–292.

Chapple, W.M., 1978. Mechanics of thin-skinned fold-and-thrust belts. Geological Society of America Bulletin 89, 1189–1198.

Chorley, R.J., Schumm, S.A., Sugden, D.E., 1984. Geomorphology. Methuen and Co, London.

Cobbold, P.R., Szatmari, P., Demercian, L.S., Coelho, D., Rossello, E., 1995. Seismic and experimental evidence for thin-skinned horizontal shortening by convergent radial gliding on evaporites, deep-water Santos Basin, Brazil. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.). Salt Tectonics: A Global Perspective. American Association of Petroleum Geologists Memoir 65, pp. 305–321.

Cooper, M.A., 1981. The internal geometry of nappes: criteria for models of emplacement. In: McClay, K., Price, N.J. (Eds.). Thrust and Nappe Tectonics. Geological Society of London Special Publication 9, pp. 225–234.

Dahlen, F.A., 1990. Critical taper model of fold-and-thrust belts and accretionary wedges. Annual Review of Earth and Planetary Sciences 18, 55–99.

Davis, D., Suppe, J., Dahlen, F.A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. Journal of Geophysical Research 88B, 1153–1172.

De Jong, K.A., Scholten, R., 1973a. Preface. In: De Jong, K.A., Scholten, R. (Eds.). Gravity and Tectonics. John Wiley and Sons, New York, pp. ix–xviii.

De Jong, K.A., Scholten, R., 1973b. Gravity and Tectonics. John Wiley and Sons, New York.

De Sitter, L.U., 1954. Gravitational gliding tectonics, an essay in comparative structural geology. American Journal of Science 252, 321–344.

Diegel, F.A., Karlo, J.F., Schuster, D.C., Shoup, R.C., Tauvers, P.R., 1995. Cenozoic structural evolution and tectono-stratigraphic framework of the northern Gulf Coast continental margin. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.). Salt Tectonics: A Global Perspective. American Association of Petroleum Geologists Memoir 65, pp. 109–151.

Elliot, D., 1976. The energy balance and deformation mechanism of thrust sheets. Philosophical Transactions of the Royal Society of London A283, 289–312.

Graham, R.H., 1981. Gravity sliding in the Maritime Alps. In: McClay, K., Price, N.J. (Eds.). Thrust and Nappe Tectonics. Geological Society of London Special Publication 9, pp. 335–354.

Heezen, B.C., Drake, C.L., 1963. Gravity tectonics, turbidity currents and geosynclinal accumulations in the continental margin of eastern North America. In: Carey, S.W. (Ed.). Syntaphral Tectonics and Diagenesis—A Symposium. University of Tasmania, Hobart, Tasmania, pp. D1–D10.

Hsü, K.J., 1969. Role of cohesive strength in the mechanics of overthrust faulting and of landsliding; reply. Geological Society of America Bulletin 80, 955–960.

Jackson, M.P.A., Hobday, D.K., 1980. Gravity gliding and clay diapirism in a Pleistocene shoreline sequence in Zululand, South Africa. American Journal of Science 280, 333–362.

Jackson, M.P.A., Talbot, C.J., 1991. A glossary of salt tectonics. Geological Circular 91-4, Bureau of Economic Geology, University of Texas at Austin.

Janecke, S.U., 1992. Kinematics and timing of three superposed extensional systems, east central Idaho; evidence for an Eocene tectonic transition. Tectonics 11, 1121–1138.

Kay, M., 1969. Thrust sheets and gravity slides of western Newfoundland. In: Kay, M. (Ed.). North Atlantic—Geology and Continental Drift. American Association of Petroleum Geologists Memoir 12, pp. 665–669.

Kehle, R.O., 1970. Analysis of gravity sliding and orogenic translation. Geological Society of America Bulletin 81, 1641–1663.

Lemoine, M., 1973. About gravity gliding tectonics in the Western Alps. In: De Jong, K.A., Scholten, R. (Eds.). Gravity and Tectonics. John Wiley and Sons, New York, pp. 201–216.

Mandl, G., 1988. Mechanics of Tectonic Faulting. Elsevier, Amsterdam.

Mann, R.J., Schultz-Ela, D.D., 1997. Effects of an inclined diapiric stem on salt flow and suprasalt deformation; examples using finite-element modeling. Abstracts with Programs, Geological Society of America Annual Meeting 29, 416.

Martinod, J., Hatzfeld, D., Brun, J.P., Davy, P., Gautier, P., 2000. Continental collision, gravity spreading, and kinematics of Aegea and Anatolia. Tectonics 19, 290–299.

Mauduit, T., Guerin, G., Brun, J.-P., Lecanu, H., 1997. Raft tectonics: the effects of basal slope angle and sedimentation rate on progressive extension. Journal of Structural Geology 19, 1219–1230.

Maxwell, J.C., 1959. Turbidite, tectonic and gravity transport, Northern

Appenine Mountains, Italy. American Association of Petroleum Geologists Bulletin 43, 2701–2719.

McGill, G.E., Stromquist, A.W., 1979. The grabens of Canyonlands National Park, Utah: geometry, mechanics, and kinematics. Journal of Geophysical Research 84B, 4547–4563.

North, F.K., 1964. Gravitational tectonics. Bulletin of Canadian Petroleum Geology 12, 185–225.

Pierce, W.G., 1966. Jura tectonics as a decollement. Geological Society of America Bulletin 77, 1265–1276.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geological Society of America Bulletin 97, 1037–1053.

Price, R.A., 1973. Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies. In: De Jong, K.A., Scholten, R. (Eds.). Gravity and Tectonics. John Wiley and Sons, New York, pp. 491–502.

Price, N.J., Cosgrove, J.W., 1990. Analysis of Geological Structures. Cambridge University Press, Cambridge.

Pusch, R., 1995. Rock Mechanics on a Geological Base. Developments in Geotechnical Engineering 77. Elsevier, Amsterdam.

Raleigh, B., Griggs, D., 1963. Effect of the toe in the mechanics of overthrust faulting. Geological Society of America Bulletin 74, 819–838.

Ramberg, H., 1980. Diapirism and gravity collapse in the Scandinavian Caledonides. Journal of the Geological Society of London 137, 261–270.

Ramberg, H., 1981. The role of gravity in orogenic belts. In: McClay, K., Price, N.J. (Eds.). Thrust and Nappe Tectonics. Geological Society of London Special Publication 9, pp. 125–140.

Root, S.I., 1973. Structure, basin development, and tectogenesis in the Pennsylvania portion of the folded Appalachians. In: De Jong, K.A., Scholten, R. (Eds.). Gravity and Tectonics. John Wiley and Sons, New York, pp. 343–360.

Rowan, M.G., Jackson, M.P.A., Trudgill, B.D., 1999. Salt-related fault families and fault welds in the northern Gulf of Mexico. American Association of Petroleum Geologists Bulletin 83, 1454–1484.

Schultz, R.A., 1996. Relative scale and the strength and deformability of rock masses. Journal of Structural Geology 18, 1139–1149.

Schuster, D.C., 1995. Deformation of allochthonous salt and evolution of related salt-structural systems, Eastern Louisiana Gulf Coast. In: Jackson, M.P.A., Roberts, D.G., Snelson, S. (Eds.). Salt Tectonics: A Global Perspective. American Association of Petroleum Geologists Memoir 65, pp. 177–198.

Siddans, A.W.B., 1984. Thrust tectonics—a mechanistic view from the West and Central Alps. Tectonophysics 104, 257–281.

Smith, A.G., 1981. Subduction and coeval thrust belts, with particular reference to North America. In: McClay, K., Price, N.J. (Eds.). Thrust and Nappe Tectonics. Geological Society of London Special Publication 9, pp. 111–124.

Smoluchowski, M.S., 1909. Some remarks on the mechanics of overthrusts. Geological Magazine 6, 204–205.

Talbot, C.J., 1993. Spreading of salt structures in the Gulf of Mexico. Tectonophysics 228, 151–166.

Temple, P.G., 1968. Mechanics of large-scale gravity sliding in the Greek Peloponnesos. Geological Society of America Bulletin 79, 687–699.

Todd, V.R., 1983. Late Miocene displacement of pre-Tertiary and Tertiary rocks in the Matlin Mountains, northwestern Utah. In: Miller, D.M., Todd, V.R., Howard, K.A. (Eds.). Tectonic and Stratigraphic Studies in the Eastern Great Basin. Geological Society of America Memoir 157, pp. 239–270.

Turner, J.P., 1996. Gravity-driven nappes and their relation to palaeobathymetry: examples from West Africa and Cardigan Bay, UK. In: Buchanan, P.G., Nieuwland, D.A. (Eds.). Modern Developments in Structural Interpretation, Validation and Modelling. Geological Society Special Publication 99, pp. 345–362.

Van Bemmelen, R.W., 1960. New views on East-Alpine orogenesis. Report 21st International Geological Congress (Copenhagen) 18, 99–116.

Van Bemmelen, R.W., 1966. The evolution of mega-undations; a mechanical model for large-scale geodynamic phenomena. International Upper Mantle Commission Symposium (Ottawa), Geological Survey of Canada, pp. 373–399.

Voight, B., 1973. The mechanics of retrogressive block-gliding, with emphasis on the evolution of the Turnagain Heights landslide, Anchorage, Alaska. In: De Jong, K.A., Scholten, R. (Eds.). Gravity and Tectonics. John Wiley and Sons, New York, pp. 97–121.

Worrall, D.M., Snelson, S., 1989. Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt. In: Bally, A.W., Palmer, A.R. (Eds.). The Geology of North America—An Overview, vol. A. Geological Society of America, Boulder, CO, pp. 97–138.

Wu, S., Bally, A.W., Cramez, C., 1990. Allochthonous salt, structure and stratigraphy of the north-eastern Gulf of Mexico. Part II: Structure. Marine and Petroleum Geology 7, 334–377.