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The engines of gravity-driven movement on passive margins: Quantifying the relative contribution of spreading vs. gravity sliding mechanisms

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ABSTRACT

Movement of gravity-driven systems on passive margins is fuelled by the loss of gravitational potential energy. Two end-member modes (gravity spreading and gravity gliding) are defined by whether the potential energy loss is due to deformation and movement towards the base of the system (spreading), or by movement parallel to the base of the system (gliding); most natural systems consist of a mixture of the two processes.

Hitherto, use of these concepts has been limited or equivocal due to lack of a quantitative measure. In some cases, characterisation of gliding vs. spreading systems based on secondary attributes has resulted in controversy, because there is a lack of consensus as to which of these are truly diagnostic. This paper presents a new, simple quantitative method based on vector analysis, providing a numerical measure of the relative contribution of spreading vs. gliding. The method is applied to synthetic examples, where deformation can be tracked, and to natural examples where a valid palinspastic reconstruction is available. The results confirm that most natural examples exhibit mixed-mode behaviour, and that some have been mischaracterized; much of the Angola margin is dominated by spreading. The method can also provide an estimate of the absolute amount of gravitational potential energy released in the movement, and the energy contribution made by gliding vs. spreading. Determining the dominant process has implications for predicting the development of seafloor topography and stratal architecture.

1. Introduction

Deformation of sedimentary sequences by gravity-driven tectonics occurs in most of the world's passive margins (Morley et al., 2011; Rowan et al., 2004) and also in other planets (Montgomery et al., 2009). Gravity-driven deformation commonly consists of thin-skinned linked systems, in which a body of sediments is translated basinwards, accommodated by extension in its updip portion, and contraction in the downdip region. This can occur on a range of scales, from small failures effecting a few metres of sediment (e.g. Alsop and Marco, 2013) to giant systems affecting bodies 10s of km thick and 100s of km long in the transport direction (e.g. Peel et al., 1995). These systems are economically important: they create structures containing substantial hydrocarbon resources (e.g. Moore, 2010). In some ways we now understand these systems very well; modern seismic data reveals their architecture; well penetrations constrain the lithology and age of the sediment sequences; sequential structural restorations reveal how the geometries we see today evolved through time. We know how the systems are powered, in a general sense: the energy source is the gravitational potential of the sediments. Energy is released as the sediments move downwards, and this powers the lateral movement and deformation. A gravitationally driven linked system from the Orange Basin margin of South Africa (Fig. 1) illustrates this principle, showing a clear separation of the updip extensional region from the downdip contractional portion. It is obvious that material has moved downwards, providing the energy that fuels the system. It is also clear that the “engine” which converts this energy into movement is complex; downward movement of sediments is achieved both by movement on the basal slip surface and by internal deformation within the body of the linked system. These two components correspond to the processes known as gravity gliding and gravity spreading, respectively (Ramberg, 1967, 1977, 1981a,b).

Distinguishing the relative contribution of gliding vs. spreading could contribute significantly to our understanding of gravity-driven systems. For example, this may determine the extent to which movement is related to sediment input to the margin, and thus whether the movement is continuous or episodic. It may determine what the rate-limiting factors are, and thus control the rate of movement. It has been suggested that both the location and the direction of propagation of the contractional toe region may be different in gliding vs. spreading systems (Brun and Fort, 2011). Rowan et al. (2000, 2004) proposed that the transition from early systems dominated by gravity gliding to younger systems dominated by gravity spreading may be an important component of the evolution of margins such us the northern Gulf of Mexico.

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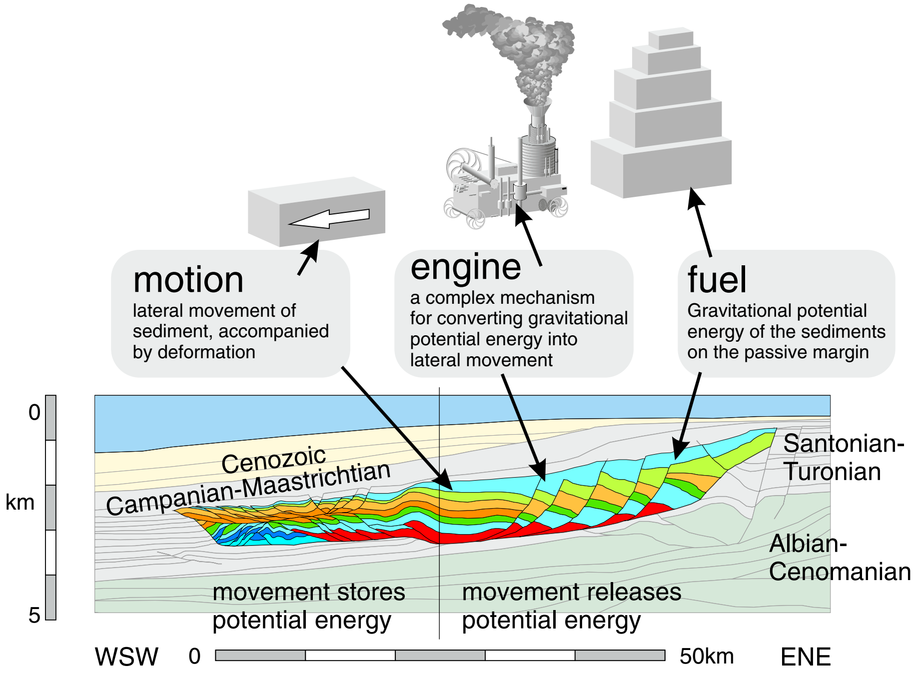

Fig. 1. A gravity-driven linked system in Upper Cretaceous sediments of the Orange Basin, South Africa, interpreted by the author. Section is in depth with 5:1 vertical exaggeration. Interpretation is based on 2D seismic reflection data; the horizons shown are correlated seismic horizons, whose precise age is not known. The gross stratigraphic correlation follows that of Brown et al. (1995) and de Vera et al. (2010).

However, in many real-world examples it can be difficult to characterize deformation as gliding-dominated or spreading-dominated using qualitative methods (Schultz-Ela, 2001), and thus our ability to characterize passive-margin deformation in these terms is limited and potentially confused, and their use has fallen out of favour.

This paper sets out a new and simple quantitative method for estimating the relative contribution of gliding vs. spreading, based on a return to the original definition of the terms. This method uses simple geometric analysis of the net movement vectors, obtained by comparing a present-day cross section with structural restorations, to determine where the energy driving the system comes from, and this alone is sufficient to characterize the amount of gliding vs. spreading. The method is generally applicable, since it is concerned only with the gross kinematics of the system and is irrespective of the lithology, rheology, fluid pressure or any of the many other factors that control the form and detailed expression of the final structure.

The method is applicable to large-scale (>1 km thickness), slow-moving systems in which kinetic energy is negligible, and is not designed for fast, catastrophic systems in which kinetic energy is significant.

2. The definition of gravity spreading and gravity gliding

2.1. The original definitions of gravity spreading and gravity gliding in mountain belts

The concepts of gravity tectonics were developed to provide a mechanism for large-scale lateral movement seen in mountain belts (e.g. Bucher, 1956; Elliott, 1976; Kehle, 1970; van Bemmelen, 1960, 1965) and the coexistence of extension and contraction in orogenic complexes (Platt, 1986).

De Jong and Scholten (1973) and Ramberg (1967, 1977, 1981a,b) defined two distinct modes of gravity-driven deformation: gravity gliding (a.k.a. gravity sliding) and gravity spreading. Ramberg (1981a) explicitly defined these terms based on the manner in which gravitational potential energy is decreased by the movement. The key words from this defining paper are reproduced here to emphasize the significance of energy to the definition: “Within most orogens … three types of structures can be distinguished; … diapirs, … nappes spread plastically over their substratum and … rock masses which have slid down inclined surfaces. These are phenomena whose immediate cause — that is, immediate driving energy — is found in the orogenic architecture itself. The structures mentioned are the results of the dissipation of gravity potential on a regional or local scale.... the energy behind the vertical sagging and complementary horizontal spreading recorded in some nappes is also a decreasing energy potential. When a nappe thins, its centre of gravity descends. That is equivalent to saying that the gravity potential of the nappe decreases as it moves. In contrast to a plastically collapsing nappe, a rock-mass sliding down an inclined surface may exhibit no … internal sagging or plastic collapse. The rock may move as a rigid unit. Again, it is evident that the gravity potential decreases during the slide”. This is made clear in the original illustrations (Fig. 2a–b).

We may restate this more simply: in gravity spreading, the energy is released by lowering of the centre of gravity due to thinning of the material. In gravity gliding, the energy is released by lowering of the centre of gravity due to movement along an inclined surface. This consideration alone is sufficient to define the terms in a manner entirely consistent with the original intention.

This return to the original intention also clarifies two other potential sources of confusion. Gliding vs. spreading are not defined either by rigidity, or by whether there is block movement. In pure gliding, the moving unit may act as a rigid block, but it may equally well experience significant internal shearing (Brun and Merle, 1985), and viscous material may also be described as gliding (Kehle, 1970), as long as movement is parallel to the base of the unit, and the base is dipping. Conversely, a spreading system may consist of multiple rigid blocks (Schultz-Ela, 2001). Of necessity, there is a component of movement parallel to the base of the unit in both gliding and spreading modes, as clearly shown in Fig. 2a–b. It is not whether there is base-parallel movement that matters, but whether that movement releases energy. In Fig. 2a, the movement parallel to the base releases gravitational potential energy; in Fig. 2b, movement parallel to the base does not release energy.