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Derivation of the area balance relations of detachment folds from first principles

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A B S T R A C T

The shortening and depth to detachment are two fundamental parameters for the construction, balancing, and restoration of geological cross-sections across fold and thrust systems. The principle of mass conservation requires both parameters to scale as the excess (uplifted) area above the original depositional level. In many occasions, however, the excess area appears to be less than the displaced (contracted) area, a phenomenon that is thought to be the product of bulk area loss, and layer thickening.

We present a derivation of Chamberlin's relation of detachment folds in which the excess area equals shortening multiplied by the depth to detachment by means of a local area-balance approach. We work out corrections for changes in bed thickness and layer-parallel compaction. Our corrections indicate the missing linear shortening scales as the wavelength of the fold. Thus, larger folds should display larger strain deficits than smaller ones. Additionally, we demonstrate that the missing strain scales as the transported area as well given rocks are compressible materials. Consequently, Chamberlin's classical relationship only holds for low-strain, relatively small detachment folds. Under this condition layer-parallel compaction, and changes in bed thickness are negligible.

We further analyze and work out corrections for the case in which sedimentary layers gradually narrow with horizontal distance; we find the stratal geometry has a strong effect on the area balance of detachment folds. Our results are in agreement with previous works, and suggests a more accurate approximation to estimate the shortening is by means of a best fit model in which the response variable is the excess area and the regressor is the average layer thickness.

1. Introduction

Map-scale detachment anticlines display simple scaling relations that emerge from the fundamental principle of continuum mechanics of mass conservation. If rocks are assumed to be incompressible, the principle requires the excess (uplifted) area, A_e, of a fold to grow in linear proportion to the shortening, u, and the thickness, h, of the detached stratigraphic successions, i.e. (Fig. 1; Chamberlin, 1910),

$$A_e = u \times h. \tag{1}$$

Thus, in a diagram A_e vs. h the shortening u corresponds to the slope of the straight line, which in principle relates these two quantities (Fig. 1; Epard and Groshong, 1993).

$$u = \frac{\Delta A_e}{\Delta h}. \tag{2}$$

The intercept of the curve with the h-axis, on the other hand, represents the detachment depth beneath the fold (Fig. 1). Relation (1) and (2) are the basis of the area-depth-strain analysis (ADS), a valuable technique to study structures detached along ductile units that works by analyzing the variation of excess structural area with depth. In many occasions, however, the uplifted area, A_e, appears to be less than the displaced area, $u \times h$, required by the mass conservation principle (Bulnes and Poblet, 1999; Koyi et al., 2003). Studies carried out in contractional deformation systems indicate the mass conservation relation underestimates longitudinal strain by as much as 25% (Butler and Paton, 2010; Sak et al., 2012). This missing strain $\delta\varepsilon$ is accommodated across the fold-belt by volume

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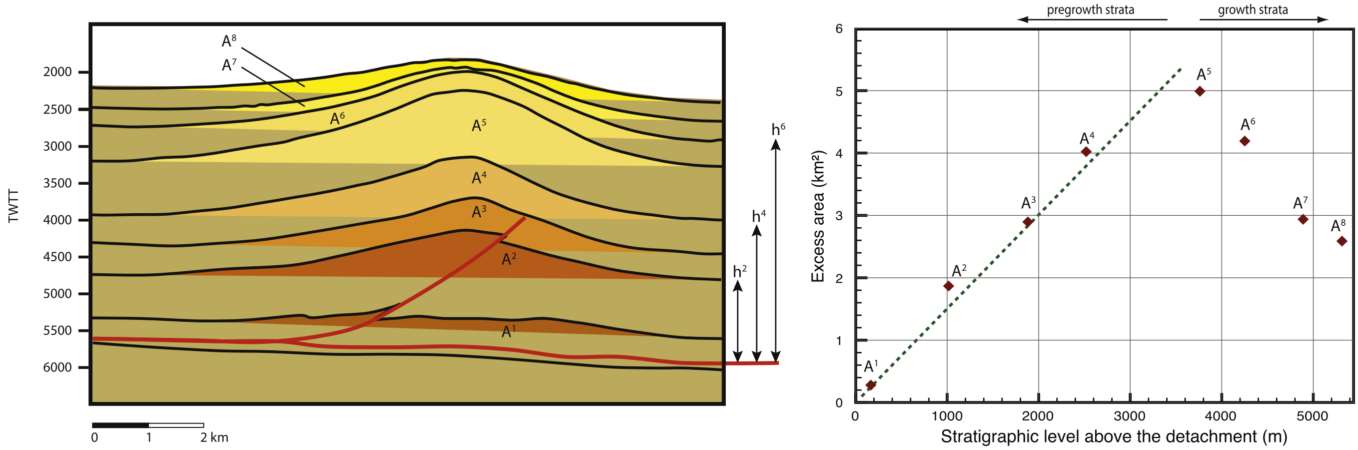

Fig. 1. Plot of the excess area *vs.* height of stratigraphic level above the detachment surface for a detachment fold in the Mexican Ridges Fold-belt, western Gulf of Mexico Basin (modified from Yarbuh and Contreras, 2015). The excess area is the uplifted part above the original deposition level or regional. The slope of the curve relating those two parameters is the shortening. Observe, however, the relation breaks down for the growth strata section due to superficial mass transport.

loss through pressure solution, porosity reduction, layer thickening, and other penetrative deformation mechanisms (Homza and Wallace, 1997; Koyi et al., 2003). Notwithstanding these complexities, analog models show the penetrative strain increases with increasing bulk shortening ε (Koyi et al., 2003). Indeed recent shortening estimations from the low-strain Mexican Ridges fold belt in the western Gulf of Mexico basin confirm these results; strain ε in this contractional system is ~10%, on average, and $\delta\varepsilon$ appears to be negligible. This means that essentially all the deformation is accommodated as excess area (Yarbuh and Contreras, 2015).

The main contribution of this paper is to present a derivation from first principles of the balancing relations (1) and (2) describing the growth of detachment folds. To our knowledge, we are not aware of any formal attempt to understand how these relations emerge from balancing laws at the sedimentary bed level and fundamental geometry axioms. This new approach allows us to derive the systematic corrections in the area balance for changes in bed thickness and layer-parallel compaction. We also establish what the limitations of the ADS method are, and predict situations in which it breaks down.

2. Derivation from first principles

Before going into the details of our new approach, it is necessary to mention first that throughout this paper we adhere to the following notation: superscript lettering refers to members of a sequence of bedding planes and layers, whereas subscripts refer to quantities at different times (with exception of excess area, which we denote by A_e). Now, the essence of the problem is illustrated by the conceptual model shown in Fig. 2: a layered medium buckling under pressure or strain from which we want to quantify the linear shortening u. Following the classical model of detachment folds, we assume a closed system in which all deformation is contained between the axial planes of the adjacent synclines, a fixed detachment surface at depth, and the folded surface of the Earth (Epard and Groshong, 1993; González-Mierez and Suppe, 2006; Contreras, 2010). We also assume buckling is accommodated by layer-parallel flexural slip and by distributed layer-parallel flexural flow which results in pure shear changes in bed thickness in the core of the structure (e.g., Hayes and Hanks, 2008; Contreras, 2010).

However, in the idealized models discussed below, we make no assumption about bed length to be constant (inextensible). Geometrically, a deformation is said to be inextensible if the arc-length of an inscribed curve is preserved. Physically, however, inextensible deformation is produced by motions in which no strain energy is induced (Kwon et al., 2005). Thus, the behavior of fabric or a piece of cord can be considered inextensible but not rocks since this class of material undergoes stretching and develop shear fractures at strains ranging from 10^{-3}–10^{-2} (Paterson, 1978).

Lets us look closely at the deformation of the control layer bounded by the bedding planes b^1 and b^2 shown in Fig. 2. The area

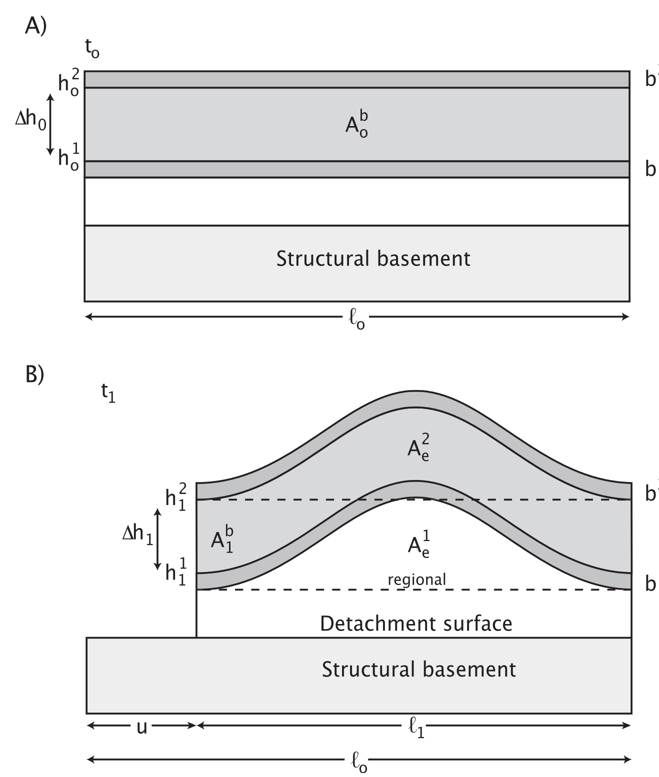

Fig. 2. Conceptual model of the development of a closed-system, homogenous thickness detachment fold. A) Configuration at $t = 0$. B) Configuration in the deformed state at $t = t_1$. The excess area in the core of the structure can be product of diapiric flow or heterogeneous pure shear. An explanation of the geometrical parameters used in the figure is provided in the text.