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Gravitational potential energy and active deformation in the Apennines

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ABSTRACT

We use velocity measurements from a network of continuous GPS sites spanning the Apennines of peninsular Italy to test the hypothesis that the active deformation of the region is explained by variations in gravitational potential energy of the lithosphere. The simple geometry of the mountain chain allows us to treat the deformation as two-dimensional, neglecting gradients of velocity along the strike of the chain. Under this assumption, the integral of gravitational potential energy per unit area of the lithosphere (GPE) in the direction perpendicular to the chain is related by a simple expression to the velocity in the same direction. We show that the observed velocities match this expression with an RMS misfit of 0.5 mm/yr. This agreement suggests that deformation of the Apennines reflects a balance, within the mountain chain itself, between lateral variations in GPE and the stresses required to deform the lithosphere. Forces arising from processes external to the belt are not required to explain the observations.

1. Introduction

It has long been recognised that the distributions of gravitational potential energy and strain rate within deforming continental regions are linked, because the growth of mountain ranges or extensional basins requires that work be done against or by gravity (*e.g.* Artyushkov, 1973; Frank, 1972; Molnar and Tapponnier, 1978). Distributions of strain rate must also, however, be influenced by lateral variations in strength of the lithosphere (*e.g.* Molnar and Tapponnier, 1981). Pieces of lithosphere whose vertically-averaged strength exceeds the stresses generated by gravity acting on density differences behave as rigid blocks, whereas weaker lithosphere deforms pervasively (*e.g.* England and McKenzie, 1983; Molnar and Lyon-Caen, 1988; Molnar and Tapponnier, 1981). While variations in tectonic style within deforming continental regions can be explained, at the scale of many hundreds to some thousands of kilometres, by variations in gravitational potential energy (*e.g.* England and Molnar, 1997; Flesch et al., 2001; Hatzfeld et al., 1997; Houseman and England, 1986), it is also clear that those patterns are modulated by the presence of strong regions, or blocks, that are embedded within the regions of distributed deformation (*e.g.* England and Houseman, 1985; England and Jackson, 1989; Vergnolle et al., 2007; Whitehouse et al., 2005). At smaller scales, it remains unclear whether deformation of the continental lithosphere is regulated by variations in its internal strength or whether the lithosphere is sufficiently weak for its deformation to be controlled by variations in gravitational potential energy.

Uncertainty in the dynamics of continental deformation has a significant impact on the analysis of seismic hazard. Velocity fields within the continents are often treated as the motions of rigid blocks (*e.g.* Hammond et al., 2011; Meade and Hager, 2005; Meade et al., 2002; Reilinger et al., 2006; Wallace et al., 2007), but if block models fail to identify all the faults that are active, then hazard will be overestimated near the boundaries of the blocks, and underestimated in their interiors (*e.g.* Aktuğ et al., 2009; Floyd et al., 2010). This epistemic uncertainty is particularly dangerous in the continental interiors, where many of the most devastating earthquakes have taken place on faults that were not previously recognised (*e.g.* England and Jackson, 2011; Stein et al., 2012; Zhang, 2013). We use a dense network of continuous GPS sites across the Apennines to address this problem at a length scale of 100 km, which is significantly smaller than the scales of 500 km and upwards of previous studies.

The Apennine mountains form an approximately linear belt, about 500 km long in the NW–SE direction and approximately 100 km wide (Fig. 1). The locus of the most rapidly slipping normal faults, and of the most damaging earthquakes, is coincident with the areas in which the surface height, when averaged on the horizontal scale of tens of kilometres, is greatest (Fig. 1). This qualitative correlation has led some to suggest that the Apennines are extending because their gravitational potential energy per unit area (GPE) exceeds that of their surroundings (D'Agostino et al., 2001, 2011). Others, however, view internal variations in GPE as

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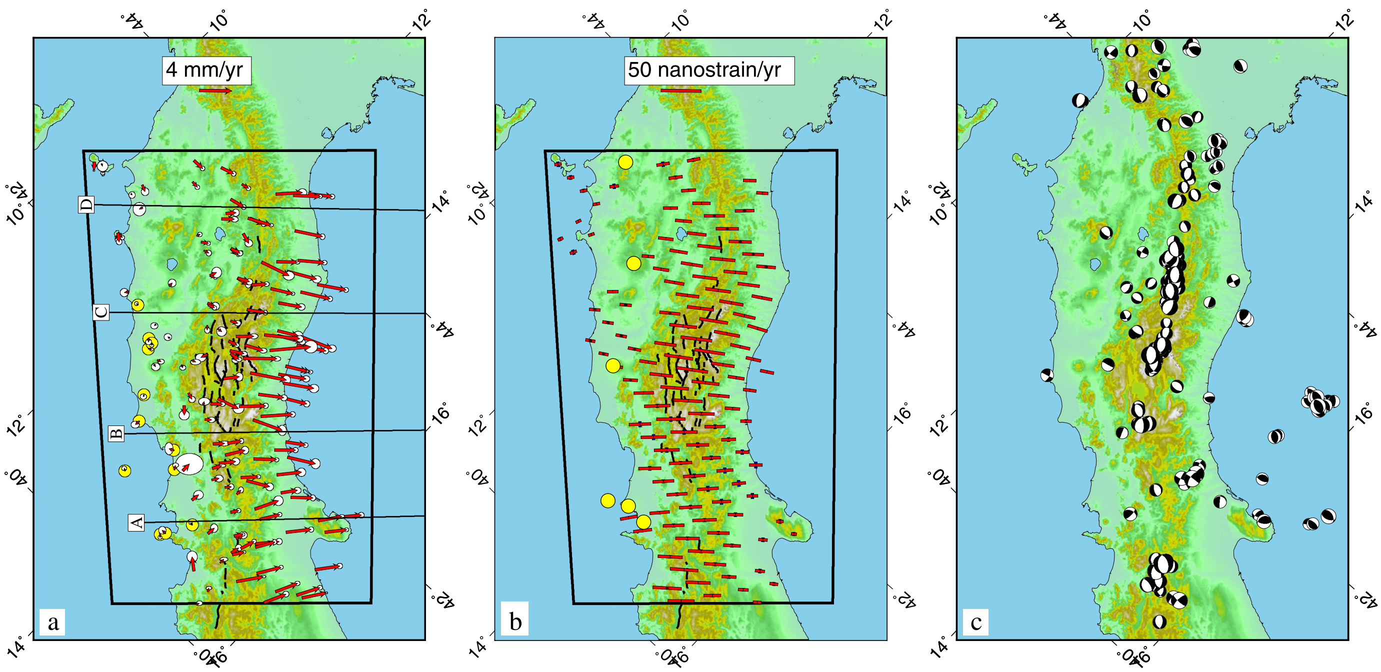

Fig. 1. Continuous GPS observations in Italy and strain rates derived from them. Boxes outline the region in which the orientations of both the velocity vectors and the principal extensional strain rate axes remain approximately constant, and which we investigate here; lines A–D show the profiles of Fig. 3. (a) Arrows show velocities of CGPS sites used in this paper in a Tyrrhenian frame of reference (Section 3.1). The sites used to establish the Tyrrhenian frame of reference are marked by yellow circles, whose radii are equivalent to 0.5 mm/yr on the scale at which the velocity vectors are drawn. Black lines show the locations of active normal faults (from Boncio et al., 2004; Galli et al., 2008; Roberts and Michetti, 2004). (b) Axes of principal horizontal extensional strain rate, derived from the CGPS data using the method of Shen et al. (1996), with a smoothing radius of 30 km. Yellow circles show the locations of Holocene volcanic centres (Siebert and Simkin, 2002). (c) Focal mechanisms of earthquakes in the Italian CMT dataset having hypocentral depth less than 30 km (Pondrelli et al., 2006). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

being negligible, and suggest that the deformation is driven by external stresses arising, for example, from the motions of nearby slabs and plates, or from convection in the mantle (*e.g.* Bennett et al., 2012; Cavinato and De Celles, 1999; Devoti et al., 2011; Shaw and Pysklywec, 2007). It has not been possible to investigate this question quantitatively in the past because the rates of extension across the entire chain are only a few millimetres per year (D'Agostino et al., 2009; Hunstad and England, 1999; Hunstad et al., 2003) and the uncertainties in velocities determined by campaign-mode GPS measurements are of order millimetres per year, rendering estimates of gradients in strain rate too imprecise for such use. Here we take advantage of the approximately two-dimensional geometry of deformation in the Apennines to recast the problem into a form that yields a direct relationship between profiles of velocities and gravitational potential energy. Then we exploit the precision and spatial resolution offered by a set of 144 measurements of crustal velocity using continuous GPS (CGPS) (Fig. 1) to test, using this relationship, whether the distribution of deformation within the Apennines can be attributed to lateral variations in gravitational potential energy of the lithosphere.

2. The signature of gravitational potential energy in a linear mountain belt

2.1. Relations between GPE and surface height

A variety of mechanisms might support the surface height of the Apennines. The long-wavelength admittance between gravity and topography suggests the variation in surface height across the mountain range is supported, at least in part, by convection in the mantle immediately below the range (*e.g.* D'Agostino and McKenzie, 1999; D'Agostino et al., 2001); this mechanism may also influence surface height through lateral variations in temperatures within the lithosphere. It is probable, however, that some of the elevation contrasts are supported by crustal thickness differences (*e.g.* Piana Agostinetti and Amato, 2009). Here we show that, for the region of interest, each of these mechanisms yields an approximately linear relationship between surface height and gravitational energy per unit area of lithosphere (GPE), so that we may carry out an analysis that is independent of the details of how the topography is supported.

We take as our reference level for GPE a column of lithosphere, of thickness L, whose crust has thickness S_0 and whose surface height is zero, adopting thicknesses of 100 km for L and 30 km for S_0. If contrasts in surface height are supported entirely by normal stresses applied to the base of the lithosphere by convection (*e.g.* D'Agostino and McKenzie, 1999), GPE differences may be approximated as the consequence of lifting the whole lithosphere by a distance h:

$$\Gamma = g\rho Lh. \tag{1}$$

Here Γ is the difference in GPE between a lithospheric column whose surface elevation is h and the reference column. The average density of the lithosphere, $\rho = \rho_c S_0/L + \rho_m(1 - S_0/L)$, where ρ_c and ρ_m are the average densities of crust and mantle; g is the acceleration due to gravity.

If surface height differences are compensated by local isostasy, then the relevant expressions for Γ are (Haxby and Turcotte, 1978; Turcotte, 1982)

$$\Gamma = g\rho_c h\left(S_0 + \left(\frac{\rho_m}{\rho_m - \rho_c}\right)\frac{h}{2}\right), \tag{2}$$

when surface height variations arise from variations in crustal thickness (Airy isostatic balance) and

$$\Gamma = \frac{g\rho Lh}{2}, \tag{3}$$