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Fault slip rate variability on 10^4–10^5 yr timescales for the Salsomaggiore blind thrust fault, Northern Apennines, Italy

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ABSTRACT

Documenting fault slip rate variability on intermediate (10^3–10^5 yr) timescales is crucial for understanding the discrepancies between short-term (10^1–10^2 yr) and long-term (10^6 yr) patterns of deformation. A major obstacle in bridging this gap has been the inability to document multi-Myr records of fault slip with 10^4–10^5 yr resolution. Here we present a 3 Myr long record of thrust fault slip with 40 kyr resolution by inverse modeling of Late Pliocene–Early Pleistocene growth strata exposed on the forelimb of the Salsomaggiore blind thrust anticline in the Northern Apennines, Italy. We augment geological data with seismic reflection and well data to construct structural models of the Salsomaggiore anticline and forelimb growth strata. We show that the deformation of the growth strata was due to slip on both a deep, late-stage, thick-skinned reverse fault and the shallow, thin-skinned Salsomaggiore thrust. We show that the thick-skinned fault slipped at a steady rate of 1.4 (+/− 0.7) mm/yr since its activation between 1.0 and 1.8 Ma, while the shallower thin-skinned Salsomaggiore thrust has slipped at rates that varied between ≤0.1 and 6 mm/yr over the last 3 Myr. The Salsomaggiore thrust exhibits a high frequency slip rate variability at 40–500 kyr timescales that is likely related to strain partitioning on connected imbricate thrusts. A major deceleration in Salsomaggiore slip rate between 1.0 and 1.8 Ma is coincident with orogenic wedge thickening due to the initiation of thick-skinned reverse faulting following the clastic infilling of the Po foreland basin during the Middle Pleistocene.

1. Introduction

Reconciling short-term geodetic (10^1 yr) and long-term (10^6 yr) geologic rates of deformation in active orogens is necessary if we are to understand strain partitioning at plate boundaries and the processes responsible for fault slip rate variability. A major obstacle in reconciling the geodetic and geologic measurements of deformation has been the difficulty in documenting fault slip on intermediate timescales (10^3–10^5 yr) with high resolution (Cowie et al., 2012; Friedrich et al., 2003; Mouslopoulou et al., 2009; Nicol et al., 2009). Here we breach this obstacle by inverse structural modeling of 3 Myr long section of growth strata with 40 kyr resolution that records the progressive deformational history of a shallow blind thrust anticline in the Northern Apennines, Italy.

Fault slip rate variability at intermediate timescales contradicts some of the classic conceptual models of long-term fault behavior. The characteristic model of fault behavior (Schwartz and Coppersmith, 1984) predicts fault slip to be steady over the intermediate timescales (10^3–10^5 yr) that span multiple seismic cycles (Shimazaki and Nakata, 1980). Alternative conceptual models suggest that deviations from characteristic fault behavior may occur and that faults may experience clustered slip events interspersed by long periods of tectonic quiescence but still exhibit the same long term slip rate as faults with regular, characteristic slip events (Wallace, 1987). Recent field and modeling studies have documented the existence of slip rate variability on intermediate timescales (Cowie et al., 2012; Friedrich et al., 2003; Gold and Cowgill, 2011; Mouslopoulou et al., 2009; Nicol et al., 2009), yet some important questions remain, such as: (1) what are the characteristic spatial and temporal scales of slip rate variability and (2) what are the underlying processes that drive slip rate variability in various tectonic settings? An essential step towards elucidating the underlying processes that drive slip rate variability is to define the characteristic timescales of variability on natural structures. In order to define the characteristic timescales of variability, continuous, high-resolution records of deformation at various timescales must be assembled. This is especially important for the intermediate timescales that span the resolution gap between short-term geodetic and long-term geologic observations. Of particular concern is the temporal gap at 10^4–10^5 yr, a resolution at which few long-term records of deformation exist (Fig. 1). Whereas most field studies (e.g. Friedrich et al., 2003; Gold and Cowgill, 2011; Mouslopoulou et al., 2009) of fault slip rate variability focus on extensional or strike-slip settings, here we examine slip rate variability for a thrust fault at intermediate timescales.

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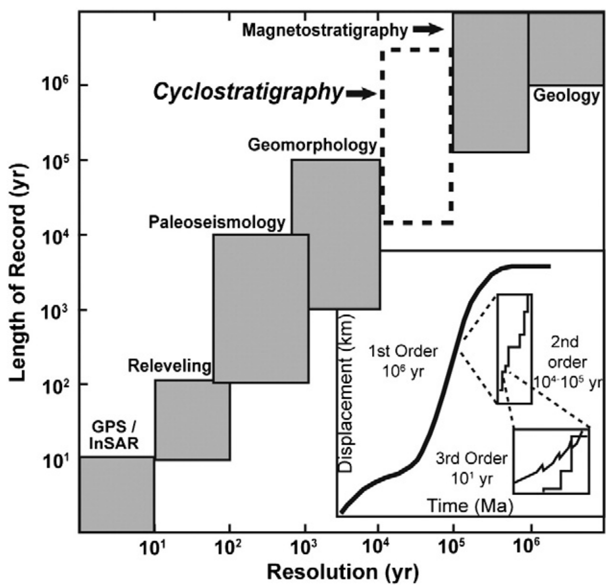

Fig. 1. The temporal resolution and lengths of record for various methods used to measure deformation are shown. Typically, as deformational records span a longer period of time, the resolution of those records decreases. The inset figure (modified from Friedrich et al., 2003) shows that structures exhibit multiple "orders" of unsteady deformation. 1st order unsteadiness is typically associated with large-scale tectonic perturbations and often documented by geologic records. 3rd order unsteadiness is related to variations in the seismic cycle. The rates and patterns of 2nd order tectonic unsteadiness are not well understood since geologic records do not have sufficient resolution and geodetic records don't have sufficient length to observe variability on the intermediate timescales.

A number of approaches are used to determine fault slip rates over different timescales. At short scales (10^0–10^1 yr), space geodetic methods using GPS or InSAR measure inter-seismic and co-seismic strain (e.g. Allmendinger et al., 2009). On longer timescales (10^6–10^7 yr), balanced cross sections with thermal or geo-chronology, magnetostratigraphy, or biostratigraphy as age controls are used to determine long-term average slip rates over the life of a structure (e.g. Robinson and McQuarrie, 2012). At intermediate timescales (10^3–10^5 yr), paleoseismology, geomorphology, and growth strata are useful methods. Paleoseismic trenching is the preferred method for understanding the most recent earthquakes on a fault segment; however, even the longest paleoseismic records are not of sufficient length to observe the full range of slip rate variability (Weldon et al., 2004). Deformed geomorphic markers such as fluvial terraces (e.g. Lavé and Avouac, 2000) record deformation with 10^3–10^4 yr resolution, but geomorphic records are commonly discontinuous and rarely extend back for more than 1 Myr in tectonically active settings.

In contrast, growth strata (Suppe et al., 1992) are good potential recorders of slip rate variability at intermediate timescales because growth strata span long periods of time and are commonly continuous. Magnetostratigraphically dated synorogenic growth strata are useful for determining slip rates on intermediate timescales but these records rarely provide a resolution better than a ~500 kyr and often the resolution is closer to 1 Myr (Charreau et al., 2008; Holl and Anastasio, 1993; Meigs et al., 1996). Cyclostratigraphy, a commonly-used geochronologic and stratigraphic method that correlates rock parameters to astronomically forced orbital cycles in sedimentary sections (Hinnov, 2000; Hinnov, 2004), has a resolution of 10^4–10^5 yr and offers the prospect of filling in the temporal gap between short-term and long-term observations of deformation (Fig. 1). In this study, we attempt to fill in the temporal gap separating the geodetic, geomorphic, and geologic observations (Fig. 1) of deformation using a section of dated growth strata exposed on the forelimb of the Salsomaggiore anticline (Fig. 2), a blind-thrust anticline in the Northern Apennines, Italy. We use progressive restorations of the growth strata to model the 10^4–10^5 resolution slip history of the Salsomaggiore thrust.

1.1. Geologic setting

The Northern Apennines and the Salsomaggiore thrust in particular are a good location to investigate slip rate variability on individual thrust faults because the Northern Apennines exhibit an apparent mismatch between the multiple observations of deformation that span different timescales. The Northern Apennines are an orogen formed by the west-dipping Adriatic lithosphere subducting beneath Europe (Jolivet et al., 2006). The orogenic wedge largely remained subaqueous throughout the Cenozoic, then became emergent in the past 1–2 Myr (Bartolini, 2003). The Northern Apennines consist of a series of imbricate thrust sheets (Pieri, 1983), with the youngest thrust faults buried under the Po Plain, some as far as 50 km north of the modern topographic mountain front (Fig. 3). At the shortest timescales, there is evidence of continued shortening on the young buried thrusts in the Po Plain as observed by GPS geodesy (Bennett et al., 2012; D'Agostino et al., 2008; Serpelloni et al., 2005), borehole breakouts (Montone et al., 2012), and historical seismicity (Ponderelli et al., 2006) including recent Mw 6.1 and 5.9 earthquakes on shallow buried thrusts underneath the Po Plain in 2012 (Cesca et al., 2013). However, industry seismic lines across the Po Plain indicate that these buried thrusts are overlain by undeformed Pleistocene deposits (Pieri, 1983, 1992) (Fig. 3). Considering the resolution of the seismic reflectors, these undeformed Pleistocene deposits suggest that probably less than ~50 m of slip has accumulated on the buried thrusts since the Middle Pleistocene. While some shortening continues to be accommodated locally by buried thrusts northwest of the Salsomaggiore anticline (Benedetti et al., 2003), most of the deformed geomorphic markers along the mountain front support the assertion that the deformation on the thrusts under the Po Plain has slowed considerably or ceased altogether and that most of the shortening since 1 Ma appears to have stepped back into the wedge and is concentrated at the present topographic mountain front (Picotti and Pazzaglia, 2008; Ponza et al., 2010; Wilson et al., 2009).

The Salsomaggiore anticline is a doubly plunging fold located at the Northern Apennine mountain front near Parma and is cored by the blind Salsomaggiore thrust (Fig. 2). The anticline presents a window through the overlying structural lid to expose deformed siliciclastic Miocene foredeep deposits (Bonini, 2007; Picotti et al., 2007) (Fig. 2). The growth of the anticline spans the subaqueous and subaerial history of the orogen. The active development of the structure was recorded by Miocene–Pleistocene growth strata deposited on the forelimb of the anticline that are continuously exposed in several river valleys (Artoni et al., 2004, 2007). The anticline is asymmetric with a steep to overturned forelimb and a gentle backlimb (Di Dio, 2005). Folding is tight near the anticlinal crest and gentle near the flanks of the fold. The shallow burial of the forelimb growth section and the lack of cleavage in the Miocene sandstone core suggest there was no major penetrative strain accumulation.

There is evidence that the Salsomaggiore thrust exhibited unsteady slip behavior during its history. Progressive and angular unconformity growth geometries observed in seismic sections show periods of both fast and slow fold growth (Figs. 3, 4). During the periods when the Salsomaggiore anticline displayed little fold growth, growth strata on the backlimb of the more foreland Cortemaggiore anticline show onlapping relationships suggesting slip that was typically accommodated by the Salsomaggiore thrust was instead being partitioned on more foreland structures (Artoni et al., 2004; Ghielmi et al., 2010) (Fig. 3). Salsomaggiore slip rates were apparently unsteady during the Middle to Late Pleistocene, as evidenced by suites of uplifted and incised fluvial terraces above the Salsomaggiore anticline that show accelerating rates of incision since 0.14 Ma for rivers flowing transverse to the anticlinal axis (Wilson et al., 2009). This acceleration follows a period of slow