Footwall drainage evolution and scarp retreat in response to increasing fault displacement: Loreto fault, Baja California Sur, Mexico

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ABSTRACT

The displacement rate history of the Loreto fault, Gulf of California, is well documented; it is characterized by episodically accelerating displacement (10 k.y. frequency) superimposed upon a period of 200 k.y. of increasing fault displacement rate. A detailed conglomerate provenance analysis in the Loreto basin records the footwall unroofing history, which has been profoundly affected by increased fault displacement rate. Clast count data capture an immediate drainage response to a significant increase in slip rate, along with the occurrence and systematic increase in abundance of a new source rock type. Our data record an increase in the rate of incision and catchment expansion associated with this increase in displacement rate. A provenance signal from a shorter-term (100 k.y.) displacement rate increase has a 30–40 k.y. lag time. No change in provenance is recorded for high-frequency (10 k.y.) variations, which are filtered out by the system.

Keywords: drainage evolution, fault displacement rate, provenance, Baja California.

INTRODUCTION

Characterizations of surface process responses to varying rates of surface deformation are a fundamental problem in landscape evolution research. The spatial-temporal evolution of normal fault arrays is well understood, and the displacement rate on discrete structures is thought to be episodic due to fault growth and linkage (Dawers and Anders, 1995; Gupta et al., 1999; Mortimer et al., 2005). Footwall uplift and associated hanging-wall subsidence have a profound influence on drainage catchment size, pattern, and yield (Leeder and Jackson, 1993; Densmore et al., 1998; Densmore et al., 2004; Cowie et al., 2006). Theoretical models suggest that the catchment response to varying displacement rate may be initially rapid but requires ~50 k.y. to reach 90% topographic equilibrium (Allen and Densmore, 2000). Despite these insights, a lack of field investigations leaves fundamental questions unanswered regarding the effect of varying displacement rate on surface processes.

This unique study provides a high-resolution field investigation into the response of a catchment to varying displacement rate. The Loreto fault has an exceptionally well-constrained displacement rate history (Dorsey et al., 1995; Dorsey and Umhoefer, 2000; Mortimer et al., 2005). We use a detailed conglomerate provenance investigation in hanging-wall sediments to investigate: (1) catchment response to 200, 100, and 10 k.y. increases in displacement rate; (2) variations in incision rate; and (3) lag time between fault activity and catchment response.

GEOLOGICAL SETTING OF THE LORETO BASIN

The Loreto basin (Fig. 1), Gulf of California, is a Pliocene half-graben bounded to the west by the NNW-SSE–striking, 35-km-long Loreto fault (Dorsey et al., 1995). Deposition is recorded by ca. 3.5 Ma (Umhoefer et al., 1994), although it probably commenced earlier (Umhoefer, 2006, personal commun.). The sedimentary fill consists of four sequences (Dorsey et al., 1995; Dorsey and Umhoefer, 2000; Umhoefer et al., 1994). Sequence 1 consists of nonmarine conglomerates and sandstones deposited during slow subsidence (0.43 mm/yr; Dorsey et al., 1995). Sequence 2 contains 16 footwall-derived fan deltas deposited between 2.50 ± 0.04 and 2.21 ± 0.05 Ma (Mortimer, 2004), during more rapid subsidence (~3 mm/yr; Mortimer et al., 2005). Sequence 3, deposited in the latest stage of rapid subsidence, consists of carbonate and siliciclastic deltas (Dorsey and Umhoefer, 2000). Sequence 4 is made up of shallow marine carbonates deposited during slow subsidence (0.4 mm/yr; Dorsey et al., 1995).

LORETO FAULT DISPLACEMENT HISTORY

The long-term displacement rate is represented by the subsidence history. A high-resolution characterization of the displacement rate history (Fig. 2) has been constrained through detailed investigations of hanging-wall sedimentary rocks (Dorsey et al., 1997; Dorsey and Umhoefer, 2000; Mortimer et al., 2005). Dorsey et al. (1997) invoked episodic fault slip in the generation of high-frequency fan-delta stacking during sequence 2. Mortimer et al. (2005) documented clinoform nucleation, from shoal-water to Gilbert-type deltas, and systematically increasing foreset height, which record 5–15 k.y. repeated episodes of accelerating (from <2 to 8 mm/yr) and later decelerating displacement rate. An overall increase in foreset height up-section possibly reflects a second-order displacement rate increase at progradational unit 6 (Mortimer et al., 2005).

FOOTWALL SOURCE AREA GEOLOGY

Paleocurrent analyses (Mortimer et al., 2005) indicate NNE transport and a SSW footwall source. Source rocks, stratigraphic ages, and geologic relations have been documented by McLean (1989) and Umhoefer et al. (2001). The principal source rock unit (after Umhoefer et al., 2001) is the Mio- cene Comundú Group, which overlies pre-Cretaceous metamorphic rocks, Cretaceous granites, and Eocene-Miocene sandstones.

The classic Comundú Group lower unit (MCL) is composed of 300 m of conglomerates and sandstones, deposited unconformably on metamorphic rocks and granites (Umhoefer et al., 2001). The Comundú Group lower unit is conformably overlain by 400–700 m of the Comundú Group middle unit (MCM) within the Sierras Gigantas, but cross sections and map relations indicate ≤500 m in the investigated area. Comundú Group middle unit rocks consist of andesitic breccias and lavas (Umhoefer et al., 2001; McLean, 1989). Lower unit or metamorphic rocks crop out along the southern margin of the granite. A possible onlap of the Comundú Group middle unit onto metamorphic rocks has been suggested 10 km north of Loreto.
METHODS

Provenance is a powerful tool for quantifying sediment source(s), drainage evolution, and lag time (e.g., Graham et al., 1988). Conglomerate clast counts were undertaken in sequence 1 (S1). Quaternary deposits: Arroyo El Leon (EL), Arroyo San Antonio, (SA), Arroyo Amarillo (AM), Arroyo Las Flores (AF). Three study areas in the Loreto basin are (1) PU1–10; (2) PU11–13; and (3) PU14. Rivers (blue) and drainage divides (dashed blue) are also shown.

Thirteen clast types (see the GSA Data Repository1) were identified and assigned to possible footwall source(s). Of these, five types were unique to specific source units and were used to infer specific source areas: metamorphic, granitic, Eocene sandstone, MCL, and MCM.

PROVENANCE DATA

Clast count data (Fig. 3) show that metamorphic clasts comprise 15%–25% of clast populations throughout the section. In Arroyo Las Flores, which sources only MCL, they comprise 40%. Granitic clasts first appear in PU13 (1%) and are present in PU14 (1%) and Quaternary deposits (5%). Eocene sandstone clasts occur at very low abundance (1%–2%) in PU7, 13, and 14.

MCL-derived clasts first occur in PU1 (3%), and their abundance notably increases after PU9. In footwall-derived Quaternary deposits, they comprise 45%–50%, but only 25% in those reworking Pliocene deltas. An absence of MCM clasts in Arroyo Las Flores agrees with stratigraphic relations. MCM clasts are present from sequence 1 to Quaternary deposits, with abundance between 40%–50% in the Pliocene, and 20%–25% in Quaternary deposits.

Non–source-specific clasts comprise the remaining populations. Those derived from dikes are present (<25%) in all counts. Those from Miocene volcanic flows are absent in Arroyo Las Flores, suggesting derivation from upper MCM and MUC rocks. Reworked shells

1GSA Data Repository item 2007161, clast types and inferred source lithology recorded in the Loreto basin, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
and unknown clasts occur at very low abundance (1%). There is little variation between the shoal-water and Gilbert-type delta of PU6.

IMPLICATIONS FOR DRAINAGE EVOLUTION

The NNE sediment transport indicates a footwall source to the SSW; however, no present-day drainage exists across the footwall. Instead, Pliocene Boulder debris-fan and Quaternary cobble alluvial fan deposits (Dorsey and Umhoefer, 2000; this study) onlap MCL rocks (Fig. 1), suggesting that a drainage did exist during the Pliocene.

Metamorphic rocks were exposed during deposition of MCL, and their occurrence without MCL clasts in sequence 1 (Fig. 3) suggests that they continued to form topographic highs. Reworking and recycling of metamorphic clasts are indicated by their high relative abundance in Pliocene deltas and Arroyo San Antonio. Their notable occurrence in Arroyo Amarillo probably reflects reworking of Pliocene deposits.

The dominant trend in the data is the upsection increase in MCL clasts, which records an increase in exposure of MCL rocks. The likely mechanism for this is unroofing, both through vertical incision and lateral catchment expansion while overlying MCM rocks were removed. In this unroofing scenario, MCM clast abundance should decrease as MCL increases; this is only observed in the Quaternary deposits, while MCM abundance in the Pliocene (including reworked Arroyo Amarillo) counts is relatively constant. This continued MCM abundance probably reflects lateral catchment expansion in the Pliocene, while the MCL increase was generated by incision. The decrease in MCM abundance in the Quaternary deposits suggests that unroofing continued until this time.

The catchment delimited by modern drainage divides is too small to provide the sediment volume preserved in the basin, particularly given the amount of footwall rocks remaining. The Pliocene catchment must, therefore, have been larger. The outcrop of metamorphic rocks in the Pliocene catchment may be traced to a low point on the modern divide (C-C′; Fig. 1), which may have contained a Pliocene drainage later captured by Arroyo San Antonio.

The occurrence of Eocene sandstone in PU7 indicates the level of vertical incision by this time. Its absence in PU8–12 and reoccurrence in PU13–14 probably reflect limited exposure and low preservation potential. Granitic rocks first occur in PU13, indicating late-stage sourcing. Map relations suggest that granite underlies MCL rocks in the footwall (Fig. 1). This is further supported by the occurrence of granite clasts in Arroyo El Leon (Quaternary), which record a granite source in this region despite a lack of modern outcrop.

INCREASED UNROOFING IN RESPONSE TO INCREASED DISPLACEMENT

The provenance data record an unroofing trend in response to footwall uplift. Here, calculated incision rates are based on the first appearance of clast types, and depositional unit (time) is based on the age and duration of PUs of Mortimer et al. (2005). MCM and MCL unit thickness has been assumed to be constant. Incision rates provide an estimate of vertical incision that most likely reflects higher-order streams.

Fault activity initiated by ca. 3.5 Ma (Umhoefer et al., 1994). Between this initiation and the first appearance of MCL rocks (ca. 2.5 Ma), ~450–500 m of overlying MCM rocks had to be removed. This yields an incision rate of ~0.45–0.5 mm/yr (slower if deposition commenced earlier).

During sequence 2, 300 m of MCL rocks overlying the granite were removed in the north of the catchment by the first granitic clast appearance in PU13 (~190 k.y. in sequence 2); this yields an incision rate of 1.6 mm/yr. The appearance of Eocene sandstone in PU7 requires 300 m of MCL removal in ~100 k.y., which equates to an incision rate of 3 mm/yr. This greater incision rate in the center of the catchment possibly resulted from greater stream power. However, these estimates do not account for lateral catchment expansion into tributaries where MCM rocks remained overlying MCL rocks.

A fourfold increase in incision rate occurred between sequence 1 and PU1 (20 k.y. into sequence 2), which we interpret to be related to increased displacement rate. A possible increase in displacement rate is inferred to have occurred during PU6 (~100 k.y. into sequence 2). While no change in provenance is apparent, a pronounced increase in MCL clast abundance occurs between PU9 and PU11 (30–40 k.y. later).

DRAINAGE EVOLUTION IN RESPONSE TO INCREASING FOOTWALL UPLIFT

We propose a model of footwall drainage evolution in response to increasing uplift (Fig. 4). At the start of fault activity (ca. 3.5 Ma), the displacement rate was low. Incision into MCM rocks (~0.45 mm/yr) was focused along drainage perpendicular to the fault, while metamorphic rocks formed topographic highs. During sequence 1, the catchment began to expand laterally, establishing tributaries within the MCM.

The displacement rate increased at the start of sequence 2, possibly due to segment linkage, whereby the displacement rate in this region of overlap would increase most (Dawers and Anders, 1995; Gupta et al., 1999). The increased displacement rate led to increased footwall uplift, which enhanced incision (1.6–3 mm/yr) and produced a near-synchronous erosional response. Between PU1 and PU6, the vertical incision rate did not increase within higher-order streams, but the catchment expanded laterally, removing MCM rocks and exposing MCL rocks in tributaries.

The possible displacement rate increase in PU6 may be reflected by increased MCL abundance between PU9 and PU11 (30–40 k.y. lag time). During deposition of PU13, granite was exposed in the north of the catchment, while the headwaters must have extended west and north of the modern-day catchment. Large boulders in alluvial facies in the footwall and immediate hanging wall indicate that a proximal source remained.

After sequence 2, we propose a drainage reorganization with capture into the Arroyo San Antonio and diversion or capture of the main stream into Arroyo de Gua. Unroofing continued into the Quaternary, recorded by significant reduction of MCM and increase of MCL.
clasts (Fig. 3). Fault scarp retreat had begun during deposition of sequence 2, as suggested by footwall alluvial deposits. The presence of a pediment surface across the basin and within the footwall, however, suggests that rapid escarpment retreat occurred during the Quaternary.

LAG TIME AT DIFFERENT FORCING FREQUENCIES

Provenance data record a near instantaneous (<15 k.y.) response to a longer-term (200 k.y.) displacement rate increase. The proposed second-order (100 k.y.) increase (PU6) resulted in an increase in MCL clasts 30–40 k.y. later (PU9–PU11). The lag time could have been due to sediment storage in the fluvial system, or the erosion response time for lesser-magnitude events. It appears that greater-magnitude displacement rate variations generate a more rapid catchment response. Recurring high-frequency events, it appears that greater-magnitude displacement rate variations generate a more rapid catchment response. Recurring high-frequency fluctuations are not recorded.

The unique Loreto basin example documents catchment evolution to varying displacement rate at typically irreversible time scales. Our new quantitative data provide insight into catchment response previously exclusive to landscape models. The rapid catchment response to long-term, high-magnitude variations, while filtering out high-frequency fluctuations, is likely to be a characteristic of normal fault footwall catchments in general.

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