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Structural evolution of the Neogene Gar Basin, western Tibet: Implications for releasing bend development and drainage patterns

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ABSTRACT

We investigated the interaction among basin-bounding faults, basin fill, and geomorphic features of the southern Gar Basin, one of only two known releasing double-bend basins along the Karakoram fault, to better understand their structural evolution and role in basin development. The southern Gar Basin is bounded by an ~44-km-long, N20°W-striking central fault segment flanked by two N40°W-striking segments that parallel the regional strike of the Karakoram fault system. The central fault segment is composed of a system of strike-slip and normal faults that young basinward and incorporate basin fill in their uplifted footwalls. The oldest faults along the extensional portion of the bend are dominantly strike-slip, and they strike ~15°W from the main strike of the Karakoram fault. Basin fill is broadly folded about a NNW-trending axis and can be explained by E-SE-directed slip along a listric normal fault. Cross sections across the basin and associated faults suggest the geometry is best described as an extensional flower structure. Forward structural modeling of the intrabasin faults shows that the system has accommodated ~8 km of east-west extension. We interpret the bend to have formed from linking of R and P shears into a through-going principal displacement zone. At shallow levels in the crust (low confining pressures), R shears are exploited; at deeper levels, these faults merge with the principal displacement zone, forming the extensional flower structure geometry. We estimate that the shear zone is 50–35 km wide based on the aerial distribution of P and R shears. Restoration of R shears on the west and east sides of the Gar Valley indicates ~55 km of right-lateral separation along the Karakoram fault, which is a minimum slip estimate for the Karakoram fault system.

INTRODUCTION

Strike-slip basins form in every structural setting from regional shortening to regional extension to transform faulting (Sylvester, 1988; Nilsen and Sylvester, 1995, 1999a and b; Mann, 2007). The complexity of these basins is attributed to a variety of factors, including: (1) evolving fault system geometry and kinematics, (2) complex stress fields, (3) configuration of preexisting structures, and (4) crustal rheology (Aydin and Nur, 1982; Mann et al., 1983; Dooley and McClay, 1997; Nilsen and Sylvester, 1999a and b; Cunningham and Mann, 2007). Although strike-slip basins have the potential to archive complex tectonic histories (e.g., Crowell, 1982; Luyendyk and Hornafius, 1987), deciphering the geologic history of ancient and long-lived strike-slip basins is challenging because of evolving deformation, uplift, and erosion patterns associated with bends in strike-slip fault systems at their margins (Spotila et al., 1998; May et al., 1993; Anderson, 1994; Bürgmann et al., 1994; Cowgill et al., 2004a).

One type of strike-slip basin is a releasing bend basin. A releasing bend basin is an area of localized extension developed along a bend on a strike-slip fault (Crowell, 1974a, 1974b). A bend is the change in continuity of the strike of a fault as it trends in one direction and then diverges. A double-bend is where the strike of the fault diverges and then returns back to the local strike. Some have interpreted releasing double-bends to have formed from the linkage of en echelon fault segments (Cowgill et al., 2004a, 2004b; Crowell, 1974a; Mann, 2007). Alternatively, regional bends could develop from the intersection of strike-slip faults, and thus slip on one fault affects the surface geometry of the other (see, e.g., Raterman et al. [2007] on restraining double-bends). Analogue models strive to capture strike-slip fault geometries (e.g., Tchalenko, 1970; Wilcox et al., 1973) and have provided a conceptual framework for understanding the shallow and deep geometry of the system (Wilcox et al., 1973; Hempton and Neher, 1986; Naylor et al., 1986; Schreurs, 1994), as well as basin development (e.g., Hempton and Neher, 1986; McClay and Dooley, 1995; Rahe et al., 1998). Dry quartz sand or powdered glass (e.g., Naylor et al., 1986; Schreurs, 1994; McClay and Dooley, 1995; Schreurs, 2003) are commonly used in these models to replicate brittle deformation in the upper crust because these materials obey the Mohr-Coulomb failure criterion (e.g., Horsefield, 1977; McClay, 1990a, 1990b). Other workers prefer to use mixtures of clay and water in their experiments to simulate more continuous deformation (Tchalenko, 1970; Atmaoui et al., 2006), especially for modeling structures in the ductile lower crust (e.g., Naylor et al., 1986). In dry sand models, Rahe et al. (1998) investigated the geometry of pull-apart basin faults at depth. In their experiments, symmetrical flower structures developed when two opposing active master faults were present, producing a full graben. Asymmetrical flower structures formed when there was a dominant master fault on one margin of the basin, yielding a half-graben basin geometry, and significant rollover of strata occurred toward the master fault (Rahe et al., 1998). The structure at depth may be complicated depending on the distribution of faults at the surface—whether en echelon or continuous, their spacing, and kinematics. Flower structures with concave-upward fault geometries are associated with dominant strike-slip displacements (Naylor et al., 1986). The geometry of the system at depth could have implications for the distribution of basin fill and drainage patterns in strike-slip basins, including those not necessarily defined as pull-apart basins.

This study focuses on the evolution of basins developed at releasing double-bends along the southern reach of the Karakoram fault system (Fig. 1) to better understand how these structures are manifested at the surface, which may help us to understand the geometry of releasing bends at depth. Between 32°30′N and 31°30′N,
the Karakoram fault system displays two releasing double-bend systems flanked by rhomboidal basins that are exposed along the Gar Valley (Fig. 1). This basin system was chosen for study because it is long-lived (several millions of years), presently active, and has not undergone significant erosion or burial due to the arid environment.

Our study focuses on the southern subbasin, hereafter referred to as the Gar Basin. Field mapping at a scale of 1:100,000, measured sections, and structural and paleoflow measurements were combined with analyses of digital topography (Shuttle Radar Topography Mission [SRTM]), multispectral (Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER], Landsat) imagery, and panchromatic (CORONA photography) imagery of the Gar Basin to better understand the evolution of the Gar Basin and strike-slip basins along double-bend systems in general.

The Gar Basin is an ~20-km-wide by ~60-km-long, rhomboid-shaped basin. It has a length to width ratio of 3:1, which is typical of most pull-apart basins (Aydin and Nur, 1982). The present-day drainage of the Gar River flows to the NW through the Gar Valley. Segments of the Gar River mimic the active-margin morphology as alluvial fans prograde basinward toward the axis of the valley. Triangular facets are common along the western margin.

Here, we provide an overview of the stratigraphic, structural, and neotectonic features of the Gar Basin. We relate the neotectonic activity to the long-term development of the basin, which is interpreted to have had an early history of linking isolated fault segments to form a principal displacement zone along the bend. We then present a forward kinematic model that explains formation of intrabasinal structures. The results from this model are integrated with geomorphologic observations to explain the structural evolution of the Gar Basin. We find that oblique-normal faulting dominates along the western margin of the basin. In this system, faults sole into a listric master fault and have initiated in a basinward sequence. This structural history and geometry can explain the pattern of relief observed along the bend, as well as the spatial relationship between the first-order drainage divides and location of active faulting.

### GEOLOGIC SETTING

Development of the Gar Basin is attributed to right-lateral slip along the Karakoram fault system (Armijo et al., 1986; Ratschbacher et al., 1994). The Karakoram fault system extends ~1000 km from the Pamir mountain ranges in the north to the Mt. Kailas area in southwest Tibet, and it is thought to have played a central role in accommodating the northward convergence of India and the southern margin of Asia (Peltzer and Tapponnier, 1988). The fault is interpreted to have initiated in the Miocene and is currently active (Armijo et al., 1989; Murphy et al., 2000; Lacassin et al., 2004; Phillips et al., 2004; Murphy and Burgess, 2006). Neotectonic activity is not recognized along its northern reaches in the eastern Pamir (Robinson, 2008; Robinson and Cowgill, 2007). Propagation of the Karakoram fault to the southeast has been suggested to have occurred ca. 11 Ma (Murphy et al., 2002; Murphy et al., 2000), although it was interpreted by Lacassin et al. (2004) to have occurred much earlier (ca. 24 Ma). Estimates of the cumulative slip on the fault are debated and range from ≥400 km (Lacassin et al., 2004) to 66 km (Murphy et al., 2000). Global positioning system (GPS) geodetic studies show that present-day slip rates range from 11 ± 4 mm/a (Banerjee and Bürgmann, 2002) to 3–4 mm/a (Brown et al., 2002; Jade et al., 2004). Mid–late Pleistocene rates of 10.7 mm/a have been reported in the Manikala Valley in the northern Gar Basin, ~37 km northwest of the mapped area, based on 10Be surface exposure dating of material from moraine crests (Chevalier et al., 2005), although this interpretation of the ages has been challenged by some (e.g., Brown et al., 2005).
actively undergoing conjugate strike-slip faulting and east-west extension (Rothery and Drury, 1984; England, 1987; Armijo et al., 1989; Taylor et al., 2003; Kapp and Guynn, 2004). To the west, there is the Himalayan fold-and-thrust belt, which is dominated by thrusting perpendicular to the trace of the Himalayan front (Molnar and Lyon-Caen, 1989; Jade et al., 2004). This dramatic change in deformation style across the fault as well as its regional extent and long life span has attracted a great deal of attention to the role of this fault in accommodating the relative motion between the Tibetan Plateau and the Himalayas (e.g., Armijo et al., 1989; Avouac and Tapponnier, 1993; Searle, 1996; Yin et al., 1999; Yin and Harrison, 2000; Replumaz and Tapponnier, 2003; Taylor et al., 2003; Murphy and Copeland, 2005).

In the vicinity of the Gar Valley, the Karakoram fault system cuts obliquely across the NW-striking Indus-Yalu suture zone, which delineates the contact between rocks with an Asian affinity to the north and those with an Indian affinity to the south (Fig. 1). From north to south, the suture zone consists of the Gangdese Batholith, Cretaceous forearc sedimentary sequence, ophiolites, and Tethyan passive-margin material in the silty intervals, and lack of imbrication in the conglomerate layers in Tcg3 also support the interpretation that these are lower-energy deposits.

Paleoflow measurements from imbricated clasts in Tcg1 indicate a paleoflow direction predominantly due east (Figs. 2A and 4). A conglomerate layer in Tcg2 contained mostly imbricated clasts that indicate a NE flow. Clasts in Tcg3 lacked pebbles with a preferred orientation, and, for the most part, paleocurrent indicators were not identified. The majority of paleoflow data obtained from Tcg4 indicate a pattern of dominant E-SE flow (Figs. 2A and 4). The youngest unit, Tcg5, is poorly sorted. Tcg5 contained few and ambiguous sedimentary structures that were not incorporated into the paleoflow analysis. The sedimentary units encountered in the measured section are interpreted as an overall eastward prograding system of sheet-flood dominated alluvial fans along the western margin of the valley. Clast composition in the conglomerate sequences is variable (Fig. 4B; see GSA Data Repository item 2009184).

**GEOLOGY OF THE GAR BASIN**

**Tertiary Stratigraphy**

Tertiary basin fill, with a minimum thickness of 800 m, consists of thick conglomeratic sequences interbedded with coarse-grained sandstone (Figs. 3 and 4). Measured sections were determined in the field with a Jacob staff along two transects in the Qiong Valley (~5 km) and Dabujia guo Valley (~7.5 km) (Fig. 2A). Clast compositions were determined by point counting ~100 clasts in 1 m² blocks along the measured section. Paleocurrents were measured from cross-bedding and pebble imbrications; however, only pebble imbrication data were used in our analysis.

Basin fill is gently deformed into a broad anticline (Figs. 2A and 3B). The stratigraphy of the measured basin fill section of the Gar Basin consists of five petromict conglomerate units defined from youngest to oldest as Tcg1 through Tcg5 (Fig. 4). The stratigraphy is divided based on contrasts in clast composition and textural characteristics. The lowermost unit, Tcg1, is composed of clast-supported, cobble-gravel-pebble conglomerate with interbedded tan coarse-grained sandstone layers up to 15 cm thick. Tcg2 is a clast-supported pebble conglomerate with interbedded thin (~8–12 cm thick), tan, medium-grained sandstone and yellow-green siltstone layers. It is capped by a phyllite-rich, uppermost clast-supported conglomerate section ~30 m thick. Tcg3 consists of clast-supported, cobble-pebble conglomerate layers up to 30 m thick and show prominent pebble imbrications (Fig. 5) with some individual conglomerate layers up to 30 m thick. The thickest documented intervals occur in Tcg4, they form steep cliffs along valley walls, and they also contain the most cobble-sized clasts.

Thick fining-upward, clast-supported conglomeratic sequences dominate the stratigraphy of the Gar Basin, suggesting a high-energy alluvial-fan paleoenvironment. Thin intervals of silt and coarse-grained sandstone, especially prevalent in Tcg3, are micaceous, suggesting lower-energy alluvial-plain facies. The lack of fossils, scarce occurrences of leaf and reed material in the silty intervals, and lack of imbrication in the conglomerate layers in Tcg3 also support the interpretation that these are lower-energy deposits.

Paleoflow measurements from imbricated clasts in Tcg1 indicate a paleoflow direction predominantly due east (Figs. 2A and 4). A conglomerate layer in Tcg2 contained mostly imbricated clasts that indicate a NE flow. Clasts in Tcg3 lacked pebbles with a preferred orientation, and, for the most part, paleocurrent indicators were not identified. The majority of paleoflow data obtained from Tcg4 indicate a pattern of dominant E-SE flow (Figs. 2A and 4). The youngest unit, Tcg5, is poorly sorted. Tcg5 contained few and ambiguous sedimentary structures that were not incorporated into the paleoflow analysis. The sedimentary units encountered in the measured section are interpreted as an overall eastward prograding system of sheet-flood dominated alluvial fans along the western margin of the valley.

Clast composition in the conglomerate sequences is variable (Fig. 4B; see GSA Data Repository item 2009184, Additional figures, description of geodatabase contents, basin fill clast count compositions, and details on data and processing methods, is available at http://www.geosociety.org/pubs/ft2009.htm or by request to editing@geosociety.org.)

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Figure 2.
Repository for detailed clast composition plots [see footnote 1]). Figure 4B shows the normalized clast counts for each unit of the basin fill differentiated into sedimentary, igneous, and metamorphic types. The clasts in Tcg1 consist largely of sandstone, white quartzite, leucogranite, epidote, pyroxenite, chert, diorite, and phyllite clasts with subordinate biotite schist, and rhyolite. Sandstone clasts are more abundant in the north, whereas phyllite is more abundant in the southern part of the mapping area. The dominant compositions in Tcg2 are red andesite, diorite, leucogranite, and gray phyllite. The upper 30 m of Tcg2 consist of abundant gray phyllite clasts. Tcg3 contains abundant leucogranite and gray phyllite, with subordinate Kailas conglomerate in the upper 27 m. The lower part of Tcg4 consists predominantly of gray andesite, quartzite, leucogranite, diorite, and gray phyllite clasts, whereas some layers contain more chert. Cobble clasts of leucogranite and sandstone are more abundant in the upper thicker conglomerate units (20–50 m). Tcg5 differs from the underlying units, since it contains angular to subangular clasts, over 16% of which are chlorite schist (more than in any of the other conglomerate units). The proximity of Tcg5 to the Gar fault and the presence of angular clasts suggest a proximal location to source material for Tcg5.

In general, there is an increase in the sedimentary and metamorphic clasts in the younger units, suggesting that the basin fill is composed of unroofing deposits (Figs. 4A and 4B). The presence of diorite, pyroxenite, granite, sandstone, gray phyllite, and leucogranite is ubiquitous in...
the basin fill and suggests that the provenance for the basin fill includes Tethyan metasedimentary rocks, Cretaceous-Tertiary granitoids, Indus-Yalu suture zone rocks, and metamorphic rocks exposed in the core of a gneiss dome in the Ayi Shan (Fig. 2A). The basin fill stratigraphy shows that throughout the history of the basin, the Ayi Shan gneiss dome was exposed and provided detritus to the basin.

Overall, the basin fill consists of growth strata as indicated by westward-thickening sequences that young toward the west. As Figure 4A shows, the thickness of Tcg4, as distinguished from the other units, is the thickest (~475 m) unit found in the west. The lower units are on average ~150 m thick. Tcg5 was only found in the northern mapped area and may thus represent localized deposition.

A single leucogranite clast from Tcg3 yielded a U-Pb zircon age of 17.82 ± 0.49 Ma (Zhang, 2009). As this is a single clast from one of the older units in the measured stratigraphy, but not the oldest, we can only deduce that the basin fill is younger than 17 Ma.

**Structural Geology**

In the study area, we defined bedrock faults as those that cut prebasin fill rock units, are oldest, inactive, and bound the basin along its western margin. We define intrabasinal structures as small-scale folds and faults that lie within the basin, cut basin fill, and for the most part appear relatively inactive. Active faults are those that cut surficial deposits and generally occur along the western margin of the Gar Valley. From satellite imagery interpretation and field relationships, these faults consist of multiple segments that cut Quaternary deposits, and thus they are interpreted to be active. We proceed with describing each major fault from west to east across the field area (Fig. 2A).

**Bedrock Faults**

There are three main bedrock faults in the Gar Basin. From west to east, these are: the Zha Jiang, Gar, and Karakoram faults. The Zha Jiang fault is the westernmost fault, and it strikes N30°E and dips ~35°SE. North of the mapped area, the Zha Jiang fault strikes subparallel to the active trace of the Karakoram fault, cutting highly fractured leucogranite. Fault striations and chatter marks indicate right-lateral oblique normal slip to the SE. The hanging wall of the Zha Jiang fault consists of Tethyan metasedimentary rocks, and the footwall consists of Cretaceous-Tertiary granite (Figs. 2A and 2B). The Zha Jiang fault merges with the Gar fault on its northern and southern ends (Figs. 2A and

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Figure 3. Photographs of key field locations. (A) Moderately dipping beds of the Tcg3 unit in the Qiong Valley. Note small house for scale (inside small white circle), ~2.5 m in height. Fault attitude is N10E, 45SE. (B) Broad anticline in the basin fill. Units thicken westward. Axis of the anticline is subparallel to the Quaternary segments of the Karakoram fault along the margin. View is to the E, toward the Gangdese Shan. (C) Segments of the Karakoram fault zone cutting Qaf deposits. Arrows point to fault scarps. View is to the W-SW. (D) Sets of conjugate faults in the Tcg2 unit. View is to the N-NW. See Figure 2A for photo locations.
Figure 4. (A) Stratigraphic column of the Gar Basin Tertiary basin fill. Basin fill consists of five conglomeratic coarse sandstone units. Tcg1 is the oldest, and Tcg5 is the youngest unit encountered in the mapping area. Rose diagrams show the dominant paleoflow direction measured from pebble imbrications at those particular intervals (dashed lines) in Tcg1, Tcg2, and Tcg4. (B) Normalized clast compositions for conglomerate sequences of the basin fill, Tcg1 through Tcg5. See GSA Data Repository item (see text footnote 1) for details on clast compositions.
suggests the fault is planar. The Karakoram fault is linear on a regional scale, it dips moderately (30–47°E). However, as the area. Along both segments, the Karakoram fault tends south of the mapped area and defines the western margin of the Gar Basin. The fault is characterized by a highly fractured zone, ~2.5 m wide, in the metasedimentary rocks, where fault striae and chatter marks indicate a right-lateral strike-slip component toward S20°E direction. The Gar fault juxtaposes basin fill against Tethyan metasedimentary rocks. As discussed in more detail later, we infer that the Gar fault is listric at depth based on the broad anticlinal geometry of the basin fill in the hanging wall (Figs. 2A, 2B, and 3B).

The Karakoram fault zone is composed of multiple parallel fault segments. The hanging wall consists of Quaternary alluvial-fan deposits, and the footwall consists of Tertiary-Cretaceous granite, and the hanging wall consists of Quaternary alluvium. The main Karakoram fault is located east of the Gar fault, bounding the high topography on the west margin of the Gar Valley (e.g., Figs. 2A, 2B, and 3C). North of the study area, it has a predominantly oblique slip to the SE and dips ~62°NE. Dip shallows to 37° near the zone of distributed extensional segments. Within the mapped area in the hanging wall, faults show predominantly normal dip-slip to the E, and dips range from 35°NE to 47°SE further south (Fig. 2A).

The Karakoram fault is linear throughout much of the mapped area, striking N30°W until it makes a sharp 30° bend, changing strike to due north in the southern half of the mapped area. Along both segments, the Karakoram fault dips moderately (30–47°E). However, as the Karakoram fault is linear on a regional scale, it suggests the fault is planar.

**Intrabasinal Structures**

The overall geometry of the basin fill is a N-NW-trending broad anticline that parallels the trace of the basin-bounding faults and narrows to the north (Figs. 2A and 3B). The anticline is asymmetric with a steeper west limb. Small-amplitude (~30–50 m) folds trend subparallel to the master fault and are distributed throughout the area.

In the northern portion of the study area (~2 km south of the Tabala Valley entrance), adjacent to the bend, faults dip 30°–50° to the north (Figs. 2A and 2B) and show oblique-slip, hanging wall down-to-the-N-NW, with some fault striae displaying dominantly strike-slip motion. In the mapped area south of the Tabala Valley and north of the southernmost Dabujiaguo Valley, intrabasinal faults strike N (~±10°) and dip steeply to the east and west. Some faults display conjugate relationships and vary in strike from 20°E to 20°W from the active fault zone (Figs. 2A and 3D). Intrabasinal faults are antithetic and synthetic with respect to the Gar fault and active Karakoram fault. Most of the intrabasinal faults dip 40–50°E-SE and display normal-dip slip, with some faults dipping 30°–40°E and showing oblique slip to the SE (Fig. 3A). Some minor faults mapped in the central area of the basin are steeper than the basin-bounding faults and have slip measurements that indicate slip to the SW (Fig. 2A).

**Active Faults**

Active faults in the Gar Valley were evaluated using spatially rectified ASTER and Landsat ETM+ scenes, CORONA photography, and SRTM 90 m data (see GSA Data Repository for geodatabase content details [see footnote 1]). Interpretations of satellite data were integrated with field mapping of Quaternary surficial deposits and faults at bends in the Karakoram fault (Fig. 6). The goal was to characterize the geometry and kinematics of neotectonic faults in the Gar Basin.

Fault scarps in the alluvial fans deposited along the western margin are easily detected in satellite imagery and can be traced along strike in the field for tens of kilometers (e.g., Figs. 3C, 6, and 7). Based on crosscutting relationships, the youngest scarps extend parallel to the mountain front, have a scarp height of 1–2 m, and are located up to 2.5 km east of the mountain front.

Active faults are prominent along the western margin of the Gar Valley (Figs. 2A and 3C). A few discontinuous faults lie along the eastern margin, but based on mapped field relationships, no significant displacement was observed. Between the towns of Zhaixigang and Menci (Fig. 1), the fault system displays two double-bend systems. Faults striking N40°W show strike-slip displacements and are localized within a narrow zone (~500 m) at the range front. In contrast, faults at extensional segments strike N10°W and are distributed across an ~2.5-km-wide zone. This fault pattern correlates to changes in slope of the range front, where steep slopes are adjacent to strike-slip segments and gentle slopes occur along extensional segments (Fig. 8).

At right-stepping, third-order bends along the western margin of the Gar Basin, we mapped four generations of alluvial-fan deposits based on surface texture, degree of incision, and reflectance. The crosscutting relationship between alluvial-fan deposits and faulting at the bends shows that faults young toward the E-SE (basinward) (e.g., Figs. 2, 6, and 7). Both strike and dip separations of Quaternary alluvial fans are observed across the active faults. Alluvial-fan generations in the west are not coeval to those found in the east because there are differences in the degree of reflectance (desert varnish), composition, and surface roughness. Only three generations were identified in the eastern margin. The source material for alluvial fans in the east consists of granitic and volcanic sediments, whereas the source for those in the west is more variable, consisting of metasedimentary, metamorphic, and igneous rocks, thus generating differences in the degree of reflectance. The alluvial fans in the eastern margin are not cut by fault scarps as are those in the west, and there is no active-margin fault.

The active front exposes the through-going character of the active Karakoram fault and delineates a nonsinusuous mountain front. The western side of the basin consists of a system of basinward prograding faults that cut alluvial fans along the margin (Figs. 2, 3C, and 6). Older fault segments are present in the basin fill and basement in the west, whereas younger segments cut Quaternary alluvial fans and moraines in the east. These segments affect the drainages by diverting them to the SE in the slip direction.
Geomorphology

Basin Characteristics

The western side is dominated by active faulting, whereas the eastern side shows no evidence of active deformation. The western margin of the basin is bounded by a series of faults that strike between N20°W and N20°E, and merge with N40°W-striking faults at a right-lateral releasing bend. Faults are characterized by oblique-normal slip to the E-SE and dip from 35° to 45°. We used SRTM data to produce a slope map of the Gar Valley and adjacent Ayi Shan and Gangdese Shan using the Topographic Modeling tools in ENVI (see GSA Data Repository item for details [see footnote 1]). Contrasting slope characteristics were detected by inspecting the first 10 km immediately west of the active margin fault. Slope map analyses of the basin reveal that the character of the western margin changes along strike of the Karakoram fault (Fig. 8): Regions bounded by NW-striking faults, which are dominantly strike-slip, show steeper slopes than regions bounded by N-S-striking faults, which are dominated by distributed dip-slip faults. Differences also exist in the character of the rock units: Strike-slip zones bound areas where basement, which consists of granitic material, is exposed adjacent to Quaternary alluvial-fan deposits; dip-slip zones are present where basin fill, which is predominantly conglomerates and sandstones, lies against Quaternary deposits, which are also conglomeratic.

Alluvial-Fan Geomorphology

The distribution and geometry of alluvial fans in the Gar Valley reflect a characteristic basin asymmetry that consists of small symmetrical fans located along the active western margin and broader shallow-gradient fans distributed along the eastern inactive edge of the valley (Fig. 7). The difference in alluvial-fan geometry implies that the margin faults exhibit some control in sediment dispersal. We will refer back to the differences in the alluvial-fan geometry of the margins to treat the concept of basin tilting with respect to the location of the master fault.

Drainage Basin

The basin is bounded by the high topography of the Ayi Shan in the west and the Gangdese Shan in the east. The drainage divide is ~12 km from the area in the mountain front defined by the active strike-slip segments of the Karakoram fault, whereas in the dip-slip zone of distributed faulting adjacent to the Gar Basin, the drainage divide is ~30 km away (Fig. 9). This difference (discussed in more detail later) is related to the interpretation that the dip-slip zone has propagated basinward, while the strike-slip zone has remained relatively stationary.

DISCUSSION

Depocenter Architecture

Previous work on strike-slip basins at releasing bends highlights the variable and complex nature of the basin fill. For example, the basin fill of the Ridge Basin in southern California displays shingled basin-margin stratigraphic patterns...
that developed as a result of a migrating point source with respect to the basin (May et al., 1993; Crowell, 2003b). Stratal geometries show that the down-dropped hanging wall supplies the majority of sediment to the basin. Alluvial-fan patterns adjacent to active releasing bends, such as in Mormon Point in the Furnace Creek–Death Valley fault system, also show that the down-dropped hanging wall supplies most of the sediment to the basin, thus yielding basin fill that contains reworked sediment from the hanging wall (Burchfiel et al., 1995; Friedmann and Burbank, 1995).

The patterns on the normalized stratigraphic column (Fig. 4A) of decreasing metamorphic clast content during the deposition of Tcg1 through Tcg3 show that footwall exhumation was, perhaps, not the dominant mechanism that provided detritus to the basin. However, during deposition of Tcg3 through Tcg5, an unroofing pattern is clearly present in the stratigraphy, as shown with increasing metamorphic clast content, suggesting that deeper parts of the fault zone were exposed. These patterns could imply that the faulting was episodic. At the time of deposition of Tcg1 through Tcg3, faulting was not as prevalent, and thus the footwall was not exhumed as during deposition of Tcg3 through Tcg5.

The nature of the basin fill of the Gar Basin provides information on the provenance as well as on the structural control of the basin-bounding faults. Coarse deposits are indicative of alluvial-fan progradation resulting from increased uplift of the footwall and increased sediment supply, whereas fining-upward basin fill deposits reflect a decrease or cessation of faulting activity. The conglomeratic sequences Tcg1–Tcg5 are interpreted to reflect an unroofing sequence that shows an increase in the metamorphic and sedimentary clasts in the younger deposits (Fig. 4). The unroofing sequence can be generalized to represent a normal unroofing sequence containing an inverted vertical clast distribution consisting of older, deeper clasts (metamorphic) in the younger units of the basin fill (Colombo, 1994). The presence of an increasing amount of sedimentary clasts further up-section suggests mixing or recycling of older basin-fill deposits. The depositional patterns suggest tectonically controlled conglomerate deposition similar to the Cutler Formation of Colorado (Mack and Rasmussen, 1984) and the Violin Breccia of the Ridge Basin (Crowell, 2003a). The conglomerate packages of the Gar Basin fill reflect episodic faulting implying that heightened periods of faulting lead to an increase in supply of coarse clastic rocks, and decreased faulting activity leads to finer-grained deposits. Furthermore, the compositional signature present in the measured section suggests progressive uplift and erosion of the footwalls of the Zha Jiang, Gar, and Karakoram faults exposing metamorphic material as well as reworked conglomerate material. The ubiquitous occurrence of igneous material in the basin fill suggests that the material is resistant to erosion and comes from a large area of outcrop. This is applicable to the Tethyan metasedimentary
rocks as well, as they are extensively exposed in the west. The youngest units mapped in the study area thicken toward the west, toward the Gar fault, as shown on the geologic map and measured section (Figs. 2A, 2B, and 4). This implies that the conglomeratic sequences developed as growth strata (Suppe et al., 1992; Schneider et al., 1996). Alluvial-fan deposition occurred concurrently with slip on the basin-bounding faults as these migrated in the direction of hanging-wall propagation, toward the S-SE, producing westward-thickening sequences of conglomeratic material. The geometry of the basin fill can be explained by a fault that is listric (shallows in the downdip direction).

Basin architecture is largely a function of the geometry of the basin-bounding faults at depth. Narrow, deep depocenters develop adjacent to planar, steeply dipping fault systems, whereas wide, shallow depocenters develop along shallowly dipping, possibly listric fault systems (Nilsen and Sylvester, 1995). From forward modeling of the intrabasinal fault system, we calculated the depth to the detachment to be ~1.2 km (discussed later herein). This satisfies the observed broad anticline geometry of the basin fill. Because the Gar depocenter was shallow, it was quickly filled with fluvial, alluvial-fan, and landslide deposits. The width of the Gar depocenter is ultimately defined by the extent of the fault zone and deposits therein from the Gar fault to the west to the recent alluvial-fan deposits of the hanging wall of the active Karakoram fault to the east.

Alluvial-Fan Geomorphologic Patterns

Strike-slip basins that form at releasing bend systems develop small catchments on the faulted side of the basin and large catchments on the unfaul ted side of the basin, suggesting that tilting of the basin floor occurs toward the active margin (Hunt and Mabey, 1966; Steel and Gloppen, 1980). For instance, in the Ridge Basin, the active margin is characterized by small talus, landslide, and steep debris-flow–dominated alluvial-fan deposits, whereas the inactive margin consists of braided stream, deltaic, and broader stream-flow–dominated alluvial-fan deposits. Tilting in the Ridge Basin occurred toward the active margin bounded by the San Gabriel fault (May et al., 1993). In Death Valley, tilting is toward the east, where the Black Mountains are bounded by characteristic small debris-flow–dominated alluvial fans, whereas larger, stream-flow–dominated fans bound the Panamint Range to the west (Denny, 1965; Hunt and Mabey, 1966; Hunt, 1975). Similarly, in the Gar Basin, small symmetric fans occur along the Ayi Shan front, and elongated, slightly asymmetric fans occur along the inactive eastern margin of the Gangdese Shan (Fig. 7). Based on this observation and comparison to other systems (e.g., Denny, 1965; Blair, 1987; Steel and Gloppen, 1980), we interpret this to mean that tilting occurs toward the active Karakoram margin fault.

The tilting of the basin floor to the west suggests that the master fault exerts control over the distribution of basin-fill deposits. The geometry of the fault system at depth consists of a single dominant margin that controls the asymmetry observed in the basin fill, alluvial-fan patterns, and fault segment distribution.
The Gar Basin deposits are constantly being modified as active faults propagate into the hanging wall, which is subsequently uplifted as the footwall (Figs. 10 and 11). Basin fill from a previous fault-basin system becomes reworked into the new fault-basin system and thus incorporates previous basin fill as well as recently exhumed rocks from deeper parts of the fault zone brought up by older, possibly active faults. This is evidenced in the conglomeratic sequences that are made up of older basin fill and material shed from the western ranges.

Fault migration in normal fault systems, such as in mainland Greece, commonly occur in en echelon configuration (Goldsworthy and Jackson, 2001). These segments could all be active at the same time, or they could be part of some sort of relay transfer of motion where the older segments are less active, or inactive, than the younger segments. From satellite image interpretation, various segments parallel to subparallel to the active Karakoram fault are found cutting alluvial-fan deposits. Older faults are stranded in the west (such as the basin-bounding Gar fault and associated intrabasinal faults), while slip is transferred to younger faults in the east. The active Karakoram fault has propagated to the east, as evidenced by the presence of multiple parallel fault scarps cutting recently deposited alluvial-fan deposits.

**Tracking the Drainage Divide**

The location of the drainage divide is an important factor in tracking active-margin fault migration. In the Gar Basin, areas where the drainage divide is closer to the margin are defined by strike-slip faulting. Although there are several sets of parallel segments, the fault zone is quite narrow (~0.5–1 km) compared to the wider zone defined by distributed normal faulting. In the zones of distributed normal faulting, the fault zone is characterized by multiple segments making up an ~10-km-wide zone (Figs. 6, 8, and 9). The drainage divide bounding the distributed fault zone is ~30 km from the active margin, suggesting that the active margin has migrated toward the east. As shown in Figure 9, the faults in the distributed zone are mobile faults that disrupt basin-fill deposits as they propagate in the slip direction of the hanging wall, to the SE. By tracking the distance from the drainage divide to the margin fault, we can conceptualize a migrating system of faults where the most active segments are found in the east. In this scenario, the drainage divide is stationary. The distance from the drainage divide to the active fault increases as the bend corner migrates in the direction of slip (Figs. 9 and 10).

In the Gar Basin, the master fault is part of a basinward-propagating system of faults. We envision the fault system affecting older basin-fill deposits by incorporating them into the new deposits as it propagates into the hanging wall in the direction of slip (Figs. 10 and 11).

**Implications for Fault Migration**

One implication of fault migration is that the preservation potential of basin fill in this system is greatly reduced as the system evolves. This is due to the active faults uplifting material that was once the hanging wall of an older system, which is then exposed to the elements to become the recycled material of the new hanging wall. This occurs throughout the evolution of
the basin as faults migrate basinward and disrupt basin fill.

Another implication is that as a result of fault migration, it will be more likely that these will merge and form smaller-scale bends. Fault migration is an important mechanism in aiding the fault system in becoming a more linear fault trace.

**Listric Fault Geometry**

The main basin-bounding fault, the Gar fault, strikes approximately N-S across the mapped area. Along most of its mapped length, it juxtaposes Tcg4 against Tethyan metasedimentary rocks (TSS). The oldest basin fill that it cuts at the surface is Tcg3, thereby limiting a straightforward assessment of its geometry at depth. In order to better understand the geometry of the Gar fault at deeper structural levels, we used cross-section C-C′ (Fig. 2) to construct a series of forward kinematic models with 2DMove structural modeling software (see GSA Data Repository item for details [see footnote 1]) that explain the observed hanging-wall deformation (Fig. 11). The primary structural feature that we attempt to explain is the basin-scale anticline. We make two general assumptions: (1) that this deformation resulted from slip along the Gar fault, and (2) no deformation to the footwall of the Gar fault occurred while its hanging wall deformed along antithetic shear planes dipping 60° to the west. This is consistent with mapped small-scale intrabasinal faults. In order to reproduce the shape of the basin-scale anticline, we calculated a geometry in which the Gar fault is listric, dips shallowly underneath the basin fill, and accumulated 1.3 km of dip-slip displacement. We calculate the depth of this bend to

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Figure 10. Fault bend–drainage system evolution model. Figure shows the development of the fault-basin system from early stages (stage 1) to present-day stages (stage 3). Drainage divide is shown as vertical dashed line. “A” denotes away from the observer; “T” denotes toward the observer. Active fault in map view and cross-section view is represented by a thick line (in map view, with a bar-and-ball symbol). The drainage basin is shown to grow in the direction of displacement (SE) by acquiring deposits from the older basins.
Gar Basin, western Tibet

be 1.2 km. Eastward, in the downdip direction, we interpret the Gar fault to steepen and merge with the downdip projection of the surface trace of the Karakoram fault. This interpretation is supported by the mapped relationship in the northern portion of the study area, which shows that the two faults merge (Fig. 2). The deformation across the section is modeled as a sequence of four stages (Fig. 11).

**Stage 1**

The key element in the initial configuration of the model consists of the Great Counter thrust dipping 30° to the west, consistent with field measurements immediately to the west of the study area (Murphy et al., 2000). We interpret that the unconformity in the Tethyan Sedimentary Sequence formed during or after slip along the Great Counter thrust and prior to development of the Gar Basin. This is supported by timing estimates on the Great Counter thrust and the presence of Tethyan Sedimentary Sequence clasts in the Kailas conglomerate (Kcg) (Yin et al., 1999; Murphy et al., 2000).

**Stage 2**

Slip along the Zha Jiang fault offsets the Great Counter thrust, which juxtaposes Tethyan

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**Figure 11.** Forward model of the evolution of the Gar intrabasinal faults. A through D indicate stages of development. Circled numbers refer to events as discussed in the text. GCT—Great Counter thrust.
Sedimentary Sequence in its hanging wall against Gangdese granite in its footwall. The trace of the Great Counter thrust must lie west of the eastern margin of the Gar Basin because only Gangdese granite crops out in the Gangdese Shan in the eastern portion of the study area (Figs. 2A and 2B). Our model assumes that the Great Counter thrust is planar and dips 30° to the west. The maximum slip on the Zha Jiang fault is determined by allowing the Great Counter thrust to be displaced as far west as possible but still expose the Gangdese granite in its footwall at the surface. In this scenario, we calculate 8.4 km of slip on the Zha Jiang fault and 5 km of extension across the model.

Stage 3

We estimated the geometry and displacement of the Gar fault from the thickness and geometry of the Gar Basin fill. The basin-scale antcline is interpreted to have formed from slip along a listric fault. We assume that the hanging wall deformed along distributed anthetic shear planes dipping 60° to the west. We calculate 1.3 km of slip on the Gar fault. We also estimate the depth to detachment to be 1.2 km. This is the resulting depth that satisfies the geometry of the basin fill on the surface and is consistent with the outcrop exposure of granite in the eastern margin.

Stage 4

Slip along the active Karakoram fault results in down-dropping of the Gar Basin fill to the east as well as displacement of the Great Counter thrust an additional 2.5 km eastward; 2.4 km of dip-slip displacement is estimated along the active trace of the Karakoram fault. The total magnitude of east-west extension calculated from this forward model is 8 km.

General Model for the 4-D Evolution of the System

Master Fault Evolution: From Isolated Segments to Through-Going Fault

In general, a strike-slip system develops from linkage of P (secondary synthetic shear fractures, passive fractures) and R (Riedel or primary synthetic shear fractures) shears that initially form a system of en echelon faults during the early stages of development of the principal displacement zone (Cloos, 1928; Riedel, 1929; Tchalenko, 1970; Wilcox et al., 1973; Sylvester, 1988). With continued development of the principal displacement zone, older fractures become inactive, and younger fractures take over deformation of the fault zone. A structural releasing bend develops after linkage of the R and P shears in order to facilitate shearing along a well-defined principal displacement zone (Fig. 12) (see, e.g., Cowgill et al. [2004b] on the development of restraining bends).

On the eastside of the Karakoram fault, a set of isolated subparallel faults extends east from the main trace of the Karakoram fault (Fig. 12A): The northermost one strikes ~N70°W, the middle one strikes ~N60°W, and the southermost one strikes ~N50°W. These are discernible as isolated right-stepping lineaments extending from the principal displacement zone in hill-shaded relief images and slope maps of the entire Gar Valley. All three faults are ~40–30 km long and are linear over their entire length (Fig. 12A). On the western side of the Karakoram fault, there is a set of faults that strike ~N20°W and are located between 31°30′N and 32°15′N; these faults are parallel to the active western margin.

We interpret the faults that strike ~N20°W to represent R shears based on their slip direction, slip sense, and angular relationship to the Karakoram fault. We interpret the inactive faults on the eastside of the Karakoram fault as P shears (Figs. 1 and 12B). P shears are oriented 35° from the principal displacement zone and are inactive structures as determined from field mapping. R shears are oriented 20°–15° from the principal displacement zone. Linkage of the P and R shears would have occurred after the development of the en echelon R and P shears because P shears are late structures and serve to link R shears (Tchalenko, 1970; Wilcox et al., 1973; Naylor et al., 1986; Sylvester, 1988; Atmaoui et al., 2006). Based on restoration of interpreted displaced R shears present in the study area (Fig. 12C), we estimate 55 km of right-lateral shear along the Karakoram fault subsequent to development of the principal displacement zone (Fig. 13). This is a minimum slip estimate because it does not take into account strike-slip along the R shears.

The upper-crustal intrabasinalbrittle faults emerge from the listric master fault and together, as a system, form a flower structure (Figs. 2A, 2B, 11, and 13). Evidence for the flower structure occurs at the surface where master fault segments curve and link to adjacent faults. In the shallow crust, the fault system manifests brittle failure in a zone composed of oblique-slip and normal-slip faults. However, we interpret from cross sections that these merge at depth, and that the dip of the principal displacement zone steepens and may be characterized as undergoing predominantly strike-slip displacement (Figs. 2A, 2B, and 13). Thus, the behavior of the master fault changes along strike from strike slip (at the N30°W-oriented segments) to oblique slip and normal-slip (along the approximately N-striking segments) in the mapping area. Furthermore, the master fault is composed of fewer segments along the strike-slip zones and multiple segments along the dip-slip zones, suggesting that the dip-slip zones are mobile, leaving inactive segments behind and forming new segments as they propagate basinward, to the SE. Thus, the principal displacement zone changes from a narrow approximately NW-striking zone to an approximately N-striking wide zone as the system migrates basinward.

The behavior of the principal displacement zone also changes with depth; at the surface, it consists of multiple segments, while at depth, these are interpreted to merge to form a shear zone that will be exposed with successive exhumation of the footwall as the system evolves. At shallow levels in the crust, where low confining pressure conditions exist, preexisting R shears are exploited, while at deeper levels in the crust, where higher confining pressure conditions exist, slip occurs on the principal displacement zone (Fig. 13). We suggest that this occurs due to a change in the style of deformation, from brittle to plastic, thus requiring a change in the yielding criterion. Figure 13C shows that at shallow levels in the crust, the upper crust operates according to Byerlee’s law, while at deeper levels in the crust, the style of deformation is ductile and therefore yielding is best described by the Von Mises criterion. This results in a change in the spatial extent of deformation; at the surface, it is distributed over a zone of ~35 km, while at depth, this zone is likely narrower. Sandbox models by Naylor et al. (1986) show a transtensional system in which subparallel Riedel shears on the surface become steeply dipping and merge at depth to a single master fault, producing a flower structure. This is similar to our interpretation of a wide shear zone occurring on the surface adjacent to the Gar bend where distributed R and P shears develop into a through-going principal displacement zone that at depth becomes narrow and possibly steeply dipping.

In a fault-bounded basin, the master fault plays a critical role in the development of the basin in terms of how it affects basin fill through its kinematic evolution at the surface and at depth. Master faults, as discussed herein, commonly involve a series of fault segments that link as the fault matures. At depth, the fault may be steep, or it may be listric and confined to the shallow crust. Furthermore, the master fault may involve both dip-slip and strike-slip components, further affecting basin-fill deposits.

In general, a master fault can be characterized as an actively propagating system where it back-steps and cuts into the footwall or frontsteps and propagates into the hanging wall. Alternatively, a master fault can be a stationary system where it remains active at a particular
Figure 12. Reconstruction of total slip along the Karakoram fault, based on restoration of R and P shears on opposite sides of the Gar Basin. (A) Uninterpreted hillshade digital elevation model (DEM) showing the present distribution of R and P shears in the Gar Valley. (B) Interpreted hillshade DEM. The width across strike of the shear zone, defined as the area bounded by the interpreted R and P shears, is 50–35 km. Gar basins are located adjacent to R shear–P shear junctions. (C) Hillshade DEM showing the restored R and P shears; 55 km of right-lateral separation along the Karakoram fault result from restoring the R and P shears. Outer dashed line shows the original location of block. DEMs were derived from Shuttle Radar Topography Mission (SRTM) 90 m resolution data. PDZ—principal displacement zone.
Stage 1:
(A) Formation of R shears and P shears. Dashed line shows future principal displacement zone (PDZ). Distribution of R shears suggests the zone of simple shear deformation related to the Karakoram fault is 50-35 km. (B) Block diagram showing PDZ, thick black line is a reference line.

Stage 2:
Development of PDZ from linked P and R shears. (A) Shows mapview and (B) shows cross-section view. (C) shows mechanical explanation. At shallow levels in the crust (low confining pressures) preexisting Riedel shears (R shears) are exploited while, at deeper levels in the crust (higher confining pressures) slip occurs on the PDZ (dashed gray line). P shears (dashed black line) may be exploited on the southern margin of the releasing double-bend system providing a path for R shears to link back to PDZ. (D) Block diagram showing merged P and R shears along the PDZ.
Figure 13. Two-stage model depicting the significance of R and P shears in the development of the principal displacement zone. The principal displacement zone forms after R and P shears link. Bends develop at the junction of the P and R shears after the principal displacement zone has fully developed as a through-going fault zone. Basins are likely to develop at these junctions. Stage 1 shows prelink configuration and block diagram. Stage 2 shows development stages for the principal displacement zone and mechanical explanation (C), where the $S_n$ axis shows increasing normal stress to the right, and $S_s$ axis shows increasing shear stress upward. Points along the circumference of the gray and black Mohr circles ($S_n$, $S_s$) represent values of normal and shear stress components. A circle tangent to a failure criterion indicates failure. Gray Mohr circle and Coulomb fracture criterion show the general case for fracturing. Small black Mohr circle and dashed frictional sliding criterion show the case for frictional sliding at low confining pressures (shallow crust), and larger black Mohr circle shows the case for slip at higher confining pressures (deeper crust).

location. An example of a stationary system is the Ridge Basin. The Ridge Basin is located at the intersection of the San Andreas and San Gabriel faults in southern California (May et al., 1993); thus, this tectonic environment may complicate its structural history. The great thickness of the Violin Breccia Formation and its proximity to the San Gabriel fault suggest that this fault remained active throughout the deposition of the Violin Breccia and did not propagate (May et al., 1993). The way in which these faults evolve characterizes the development of the master fault as a basin-bounding system by influencing the depositional environments. For instance, a master fault that propagates into the hanging wall will cut through basin-fill deposits, and as the fault slips, these will fill the gap produced, resulting in sequences of growth strata (e.g., Suppe et al., 1992) that young toward the fault. A master fault that back-steps into the footwall will cut into the footwall, and uncut basin-fill deposits in the hanging wall will onlap against the fault and get progressively younger away from the principal displacement zone. The conglomeratic sequences of the basin fill are younger and thicker toward the Gar fault in the west, corroborating the presence of growth strata in the basin fill.

General Releasing Bend Model

The rhomboid geometry of the Gar Basin is comparable to the classic pull-apart geometry (Aydin and Nur, 1982; Sylvester, 1988; McClay and Dooley, 1995). However, its evolution differs in that only one active margin is present, and the master fault is listric, as shown in block diagram form in Figure 14. In the early stages, linkage between preexisting R and P shears occurred to form a through-going strike-slip fault zone. After the R shears linked, slip along the bend was predominantly normal dip-slip, with a small component of strike-slip, rather than pure strike-slip. The Gar Basin evolved from a bend in a through-going fault rather than from a stepover pull-apart. The latest stages of basin development involve faults migrating from west to east (basinward), as is evident in the recent fault scarp of the active Karakoram fault that are found in Quaternary alluvial-fan deposits and moraines. These younger faults facilitate the smoothing out of the master fault as it evolves into a more linear trace (the northern Gar Basin is bounded by a straighter margin fault, whereas the southern Gar Basin is bounded by multiple faults that tend to curve the master fault trace). At depth, the Zha Jiang, Gar, and Karakoram faults merge onto a listric master fault that may steepen at depth into a narrow shear zone forming an asymmetric flower structure. The asymmetry of the basin is accounted for by the alluvial-fan patterns, which suggest that tilting occurs toward the active margin, and by the distribution of fault segments on the surface. Basin-fill deposits have been modified by a propagating system of faults and displaced in the dip direction, toward the S-SE, giving rise to a broad intrabasinal anticline.

This study presents research on the development of releasing bend basins bounded by listric master faults that are part of extensive strike-slip systems. Furthermore, by studying the aerial distribution of fault systems associated with what constitutes the fault zone, or principal displacement zone, we can understand the evolution of shear zones and to what extent they control basin development in strike-slip fault systems. This study has led to the recognition of a new type of basin: a releasing double-bend basin(s) bounded by a listric master fault that is present along a single margin.

CONCLUSIONS

This study integrated detailed field mapping and analyses of digital topography (SRTM), multispectral (ASTER, Landsat) imagery and panchromatic (CORONA photography) imagery of the Gar Basin area in order to better understand bend evolution, drainage pattern development, and depocenter migration in a releasing bend basin. Our main results are: (1) active faults are only present along the western margin of the basin; (2) the bends bordering the Gar Basin have propagated toward the transport direction of the basin-bounding normal faults; (3) the oldest faults bounding the basin are dominated by strike-slip displacement accompanied by later-stage normal slip; and (4) the drainage divide on the faulted side of the basin lies farther than expected from the trunk stream in the basin. These results imply

Figure 14. Gar Basin–Karakoram fault system block model. Diagram shows the development of the basinwide anticline as the system slips S-SE along a listric fault. Arrows outside the block show main strike-slip motion. Long dashes on top surface indicate pre–strike-slip position of merged P and R shears. Fault sequencing shows 1 as the oldest and 3 as the youngest.
that evolution of the basin has been strictly governed by the geometry and history of the margin fault system, its geometry at depth, and kinematics through time. The faults in the Gar Basin are interpreted to have developed from linkage of R and P shears, which led to a change in kinematics along the bend from predominantly strike-slip along the older R shears (e.g., basin-bounding Gar fault) to oblique-normal slip along the younger R shears (intrasubductional). The drainage basin area has thus increased with time growing in the direction of basin propagation. The active basin extends from the active Karakoram fault and east of it for ~15 km, while the shear zone may extend up to 50 km based on the aerial distribution of P and R shears. The preservation potential of basin fill in this scenario is low due to limited burial of the basin fill, strike-slip motion along the active Karakoram fault zone, and an active basinward stepping system of oblique-slip faults. Furthermore, older basin fill is subject to uplift, erosion, and reworking into younger basin fill.

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