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Scaled Sandbox Modeling of Transtensional Pull-Apart Basins—Applications to the Coso Geothermal System

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ABSTRACT

Results of a sandbox modeling program investigating transtensional strike-slip pull-apart basins are presented in this talk. The models are designed to investigate gross basin architecture as well as intra-basin deformation and compare the results to the structural setting of the Coso Geothermal System. The base geometry of the Coso system has been approximated to a 30º releasing stepover. In the models this geometry is approximated by cut aluminum plates linked by a stretching rubber membrane to generate intra-basin extension and subsidence. The Coso pull-apart is further complicated by a degree of transtension across the system and this is modeled by a 5º divergent oblique-motion across the master strike-slip faults. Brittle cover rocks are modeled by fine-grained (100 μm) silica sand and ductile layers by silicone polymers. Single polymer layers model a conservative brittle-ductile transition in the Coso area at 6 km. Dual polymer layers impose a local rise in the brittle-ductile transition to 4 km depth.

In all models the gross geometry consists of a lazy-Z shaped basin consisting of terraced sidewall fault systems and a cross-basin fault zone (CBFZ) linking the offset principal displacement zones. Models conducted with symmetric displacements on the moving plates generated intra-basin horst structures that separated dual depocenters. Variations in displacement ratios on the master plates resulted in the development of asymmetric basins with distinctly terraced margins on the low-displacement plate and dissected by cross-basin fault zones with complex horst structures. The addition of a high-level localized polymer layer serves to concentrate deformation further along the CBFZ. In these models the CBFZ is a narrow, deep, graben structure that links the PDZs flanked by low displacement margins and segmented horst structures.

The results of the modeling program bear strong resemblances to the structures seen on the ground at Coso. Intra-basin highs such as the Coso Range are generated in the pull-aparts and the geometry and location of these highs is dependent on the imposed boundary conditions. Basin asymmetry is strongly linked to variations in relative plate motions. Future modeling will seek to generate 4D evolutionary models of these pull-apart structures using models “frozen” at various displacements as well as detailed analysis of surface deformation using high resolution laser scanners that rapidly generate large data clusters at each increment of deformation.

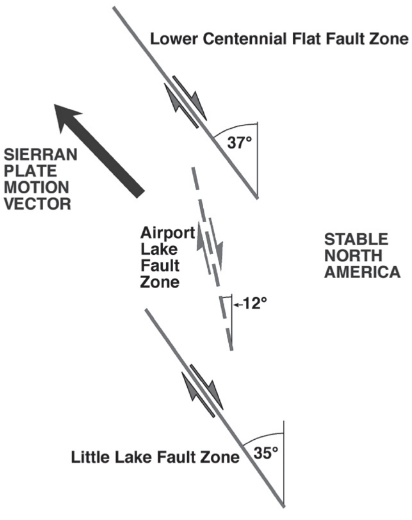

Figure 1. Highly simplified, synoptic, figure of the Coso releasing step illustrating the main fault zones and oblique displacement vector.

Introduction

The current accepted structural model for the Coso Geothermal System (CGS) is that it has developed within a pull-apart structure complicated by a transtensional element across the basin, i.e. the motion vectors of the basin sidewalls are not parallel to the bounding principal displacement zones but anticlockwise-oblique leading to divergence (Figure 1). The CGS is locally developed along the Airport Lake-Coso Wash fault system that forms a cross-basin fault zone linking the offset bounding structures (Monastero, pers. comm.; c.f. Dooley & McClay, 1997). Cross-basin fault systems have been developed in analog models of pull-apart basins and prove to be complex zones of localised uplift and subsidence disrupting the floor of pull-apart basins (Dooley & McClay, 1997; Dooley et al., 2003, 1999; McClay and

Dooley, 1995; Rahe et al., 1998; Sims et al., 1999). Studies by Wesnousky (1988, 1989) indicate that with increasing displacement and thus maturity, strike-slip fault zones have a tendency to straighten themselves, probably due to the formation of cross-basin (and uplift cut-off) fault systems. These fault systems were also defined as 'basin cutoff' faults (Burchfiel et al., 1989), and have important implications in the development of the basin system (e.g. localization of fluid flow; segmentation of the basin floor) as well as possible dissection and ultimate 'death' of a pull-apart basin. This study will seek to better understand the 3D architecture of these cross-basin fault systems in transtensional pull-apart basins.

Results of a scaled analog modeling project investigating the structure, evolution and kinematics of the Coso Geothermal System are presented in this talk. The research project aims to generate analog models of transtensional pull-apart basins in homogeneous and inhomogeneous media with a major focus on the development and 3D geometry of intra-basinal fault systems analogous to the Coso Wash fault system that controls the geothermal field. In-house studies by the Geothermal Program Office and others (e.g. Unruh et al., 2003) have indicated that the CGS is located within a pull-apart basin structure similar to models presented by Dooley & McClay (1997). The 'best-fit' model is an under-lapping, 30°, master fault arrangement described by Dooley & McClay (1997) although the introduction of a 5° transtensional component complicates the geometry of the CGS.

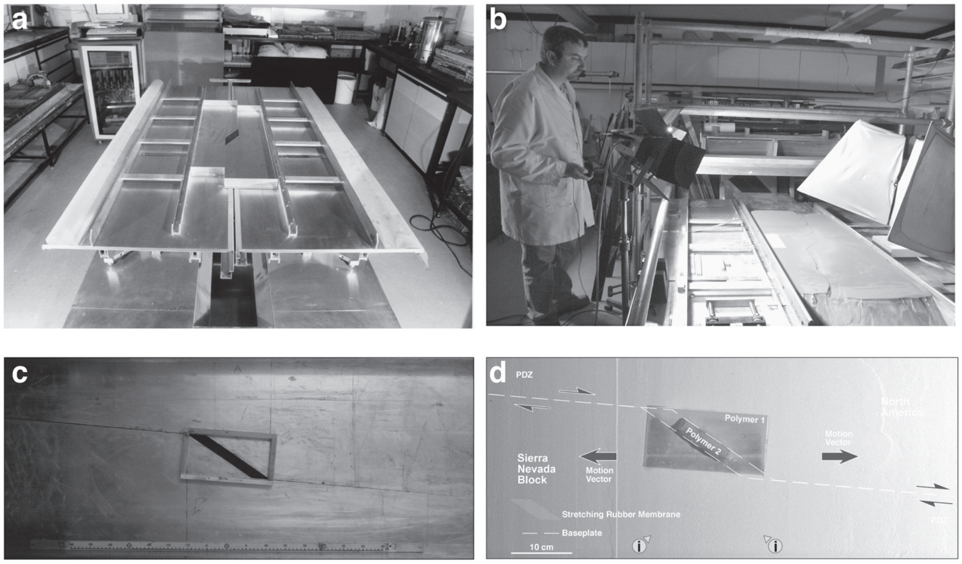

Figure 2. (a) Photograph illustrating the deformation rig with strike-slip stepover plates; (b) Photograph illustrating the deforming sandpack during a model run; (c) Photograph of the stepover region and frame containing polymer for single polymer models. Frame is removed prior to the addition of the brittle overburden; (d) Photograph illustrating polymer set-up for dual layer models. Secondary, high-level, polymer layer is highly localized.

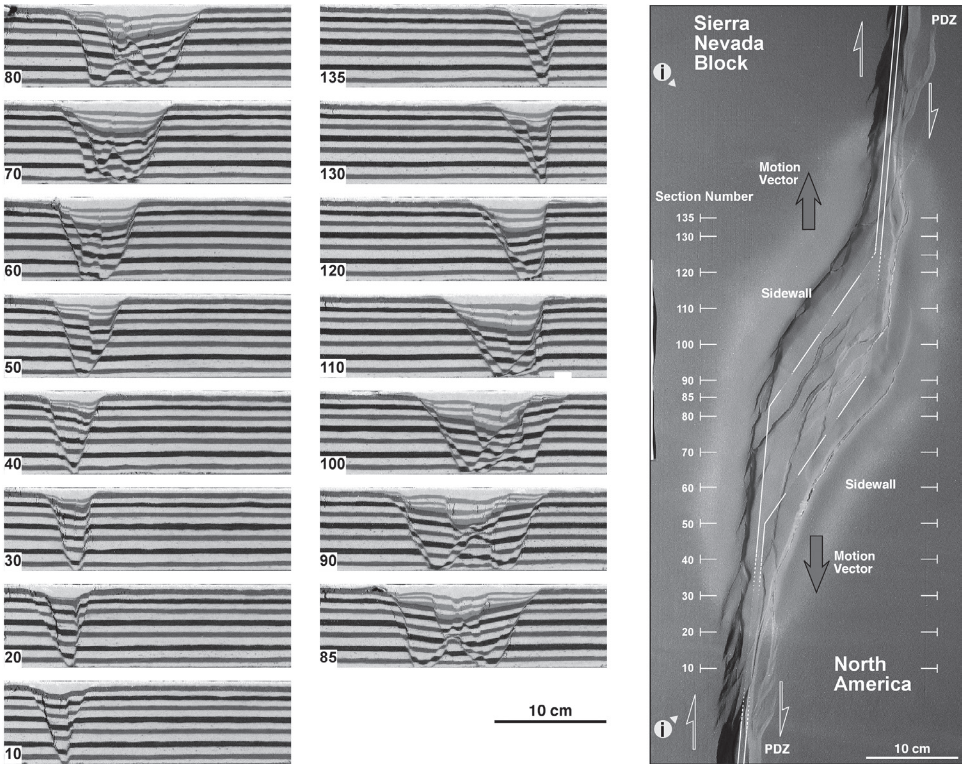

Figure 3(a). Final overhead view of a sand only model (Coso-10) and serial sections through this model.

Methodology

Models have been conducted on a computer-controlled deformation table and monitored by time-lapse digital photography (Figure 2). Baseplate set-up consists of a 30° releasing stepover that approximates the geometry of the Coso pull-apart structure (e.g. Dooley et al., 2003; Unruh et al., 2003) cut into aluminum plates and linked to the moving walls of the deformation rig. For most of the model runs a stretching rubber membrane was attached to the plates to generate differential extension across the pull-apart structure. Transtension was introduced across the developing pull-apart by imposing 5° oblique motion to the plates that make up the boundaries to the strike-slip master faults (Figure 2). The upper crust was modeled with silica sand with an average grain size of 90µm and a thickness of 7.5 cm. In dual-layer models a ductile layer was introduced locally to cover the stepover region with a thickness of 1.5 cm

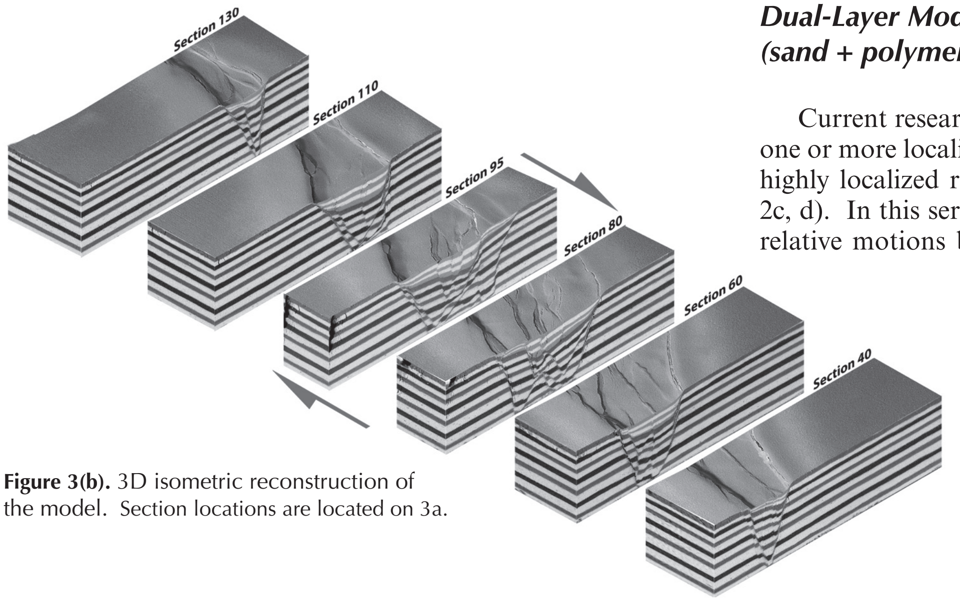

Figure 3(b). 3D isometric reconstruction of the model. Section locations are located on 3a.

thus shallowing the brittle-ductile transition to a conservative 6 km (scaling of 10^{-5}; 1 cm = 1 km), and distributing the strain across a broader zone in the overlying sand-pack. Dual polymer layers consist of the set-up described above combined with a highly localized ridge of high-level polymer across the center of the pull-apart (Figure 2). Completed models are gelled and serially sectioned at 3.0 mm increments allowing animation of the pull-apart basin development and the highly variable cross-sectional geometry of the structures

Model Results

Single-Layer Models (sand only) – 5° Transtension

Typical geometry of single layer models consisted of a lazy-Z shaped rhombochasm bounded by arcuate oblique-extensional sidewall fault systems. Basin sidewall fault systems consist of a series of hard- and soft-linked segments that define the outer limits of the pull-apart (Figure 3a). Internal deformation consists of a *cross basin fault zone* (CBFZ) that dissects the basin floor and divides the structure into two half-graben systems. 3D reconstructions of this model illustrate the rapidly changing geometry of the pull-apart along strike, the steep basin margin fault zones and the complex CBFZ (Figure 3b). The transtensional component generates *principal displacement zones* (PDZ) that are broader than those produced under PDZ-parallel displacement/extension and are composed of distinct en-echelon segments that display geometries with characteristics similar to those seen in analog models of oblique rift systems (Figure 3a; e.g. McClay et al., 2002.

Dual-Layer Models (sand + polymer) – 5° Transtension

Current research focuses on multi-layer systems, whereby one or more localized polymer layers represent basin-wide or highly localized rise in the brittle-ductile transition (Figure 2c, d). In this series of experiments the other variable is the relative motions between the "Sierra-Nevada" and "North American" plates. Results of model runs in these series display broadly similar geometries (i.e., central horst blocks, terraced sidewalls) to those features seen on the ground at Coso.

In single-polymer runs (1.5 cm thick basal polymer layer; Figure 2c), an arcuate, oblique-extensional fault typically curves outward from the principal displacement zone (PDZ) and tips out at the lateral margin of the structure to form the longitudinal boundary of the pull-apart (Figure 4). Between this structure and the basin floor another arcuate oblique-extensional fault system with major displacement links the offset PDZs. These two oblique-extensional fault systems are typically composed of several segments that display breached soft-linkage structures along their length (Figure 4). A major cross-basin fault zone (CBFZ) dissects the basin floor and divides the basin into two, relatively symmetric, half-graben structures (Figure 4). The CBFZ commonly manifests itself as a plunging, horst-like, structure bounded by these oblique-extensional faults that dip toward the sidewall faults of the pull-apart basin (Figure 4). Models in this series indicate that the geometry and relative symmetry of the CBFZ varies

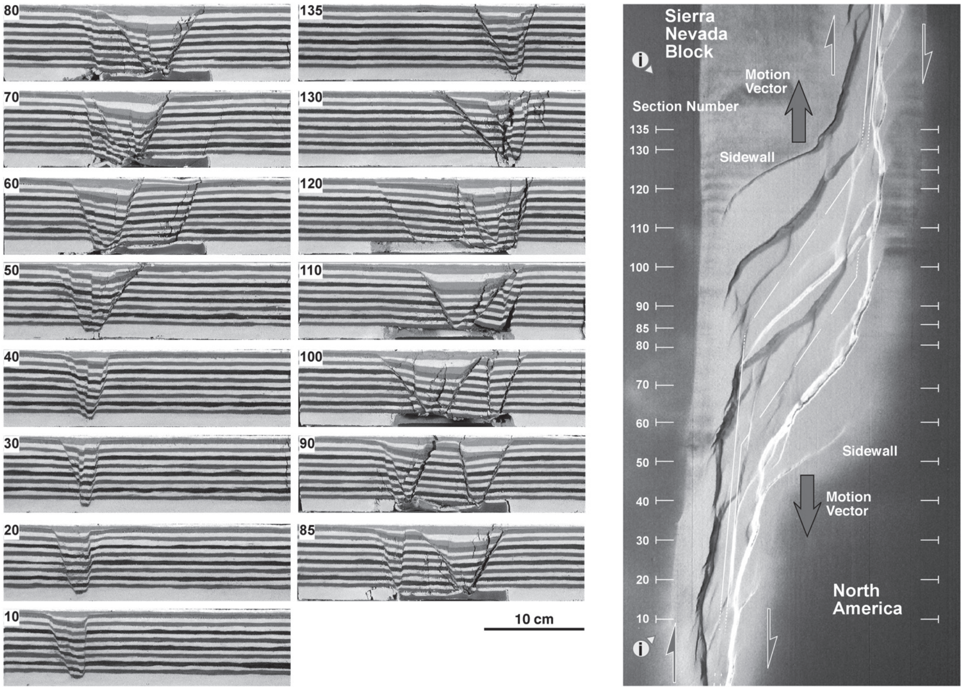

Figure 4. Final overhead view and serial cross-sections through a single polymer layer model (Coso-12a) with symmetric displacement on both plates.

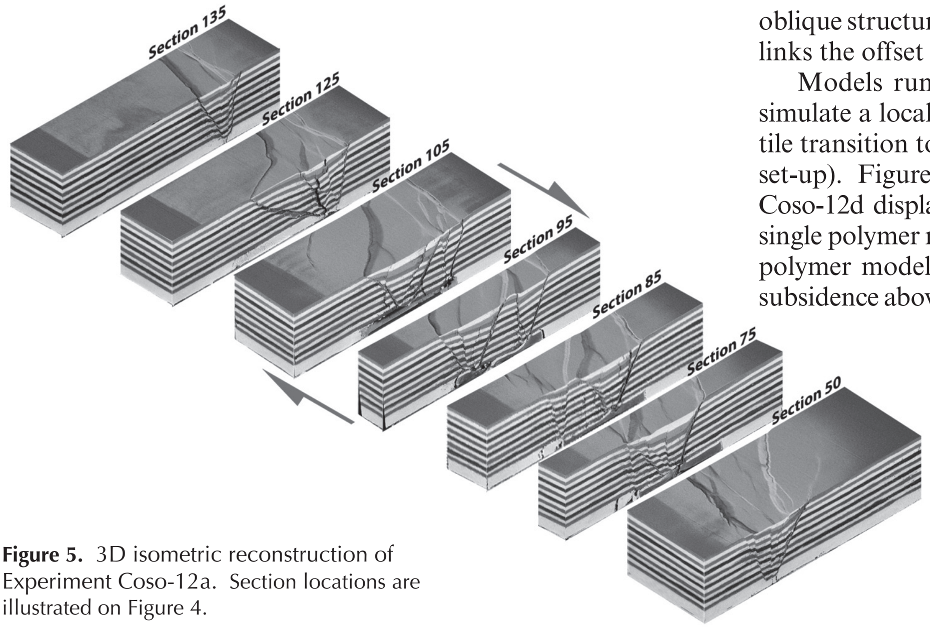

Figure 5. 3D isometric reconstruction of Experiment Coso-12a. Section locations are illustrated on Figure 4.

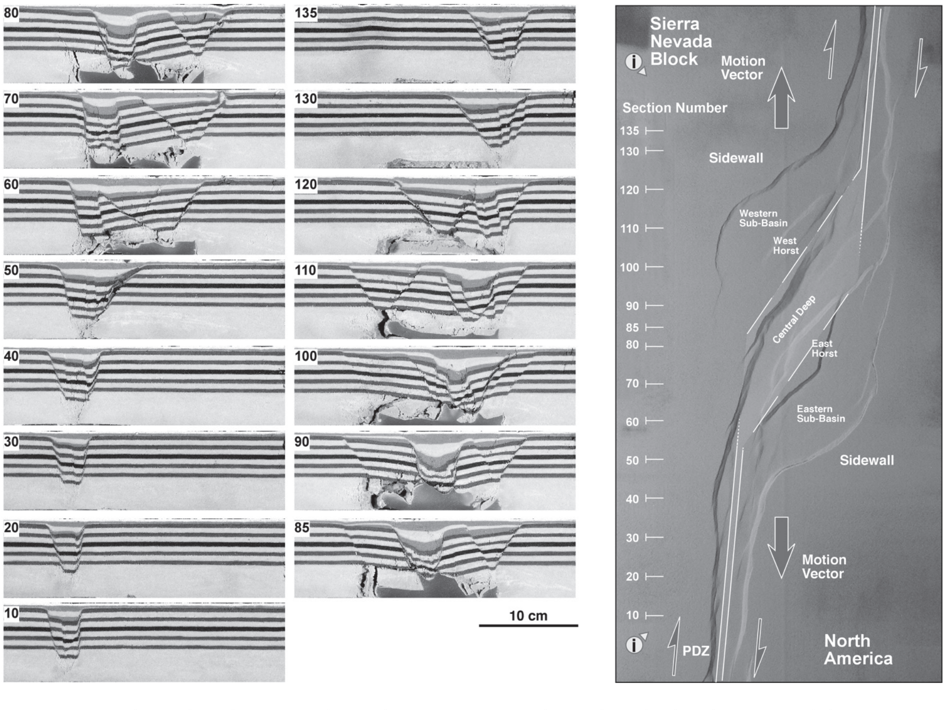

Figure 6. Final overhead view and serial cross-sections through a dual polymer model (Coso-12d), run with symmetric displacement on both plates.

according to the relative motion between the two plates that make up the tectonic system. Serial cross-sections through the models illustrate the rapidly changing structure along strike, and clearly demonstrate the horst-like nature of the CBFZ and the role this structure plays in dissecting the basin (Figure 4). Serial sections also demonstrate the highly dilational natural of the major fault zones within the pull-apart structure, and thus the role these structure would play in fluid transfer. A 3D isometric reconstruction of this model is presented in Figure 5, illustrating the rapidly changing structure of the pull-apart along strike. The central horst block is clearly seen as an oblique structure that forms major relief on the basin floor and links the offset basin sidewall fault systems (Figure 5).

Models run with dual-polymer layers were designed to simulate a localized intra-basin shallowing of the brittle-ductile transition to approximately 4 km depth (see Figure 2d for set-up). Figure 6 illustrates the final geometry of experiment Coso-12d displaying a broadly similar geometry to those seen in single polymer models. There are distinctive differences. Dual polymer models demonstrate much stronger localization of subsidence above the high level ductile zone resulting in the development of a cross-basin "deep" (graben) that links the offset PDZs. This is clearly seen in the overhead, cross-sectional and 3D isometric views (Figures 6 & 7). This structure is flanked by distinct horst structures separating the central graben from the shallow graben and half-graben structures that make up the eastern and western sub-basins of the pull-apart. The 3D isometric reconstruction illustrated in Figure 7 illustrates reactive rise of the polymer layer in the footwall to this central graben structure. The flanking horst structures are clearly seen in Sections 65-110 and strata in these horsts dip toward the central graben (Figure 7).

Distinct differences in horst development in the basins of Figures 4 and 6 are clearly seen in 3D reconstructions of the upper surface of the pre-kinematic sandpack (Figure 8). Single polymer layer models demonstrate a major horst structure that bisects the basin and separates two distinct subbasins that define the deep depocentres of the pull-apart (Figure 8a). These depocentres are separated from the basin margins by a terraced fault system, consisting of major basin-ward dipping relay ramps (Figure 8). In contrast dual-polymer layer models generate a lazy-Z shaped, steep-walled narrow graben that forms a continuous structure across the basin, linking the offset PDZs (Figure 8b). This structure forms the deepest portion of the basin and is flanked in the center of the basin by horst structures that separate this central 'deep' from the terraced margins of the pull-apart basin.

Discussion and Conclusions

Sand-polymer models run during this study compare very favorably with the CGS, enabling direct comparison between structures such as the Coso Wash Fault/Coso Range and structures observed along the CBFZ. Overlays of model results on Landsat TM and structural maps produce striking similarities in gross structural geometries. Despite significant variables tested in the models (plate-motion asymmetry, single- or dual-polymer layers) the gross geometry of the pull-apart basin remains constant, broadly described as a segmented lazy-Z-

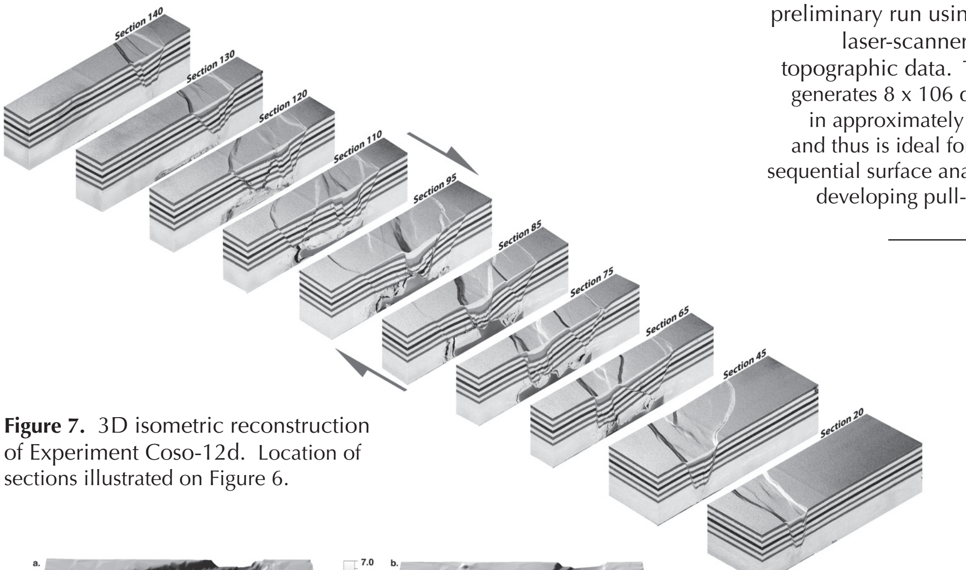

Figure 7. 3D isometric reconstruction of Experiment Coso-12d. Location of sections illustrated on Figure 6.

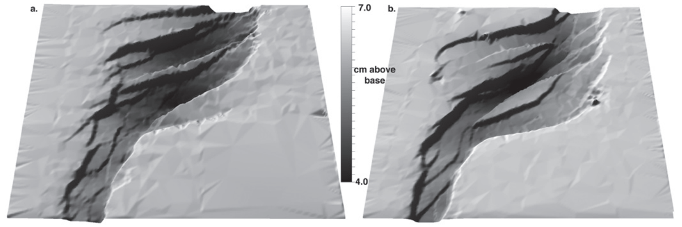

Figure 8. 3D reconstructions of the upper surface of the pre-kinematic strata from experiments Coso-12a (a), and Coso-12d (b). Note the dual depocenter geometry of Coso-12a whereas subsidence in Coso-12d is concentrated along the CBFZ. See text for further details.

shaped basin transferring displacement from PDZ to PDZ. Intra-basin deformation however, is strongly dependent on the boundary conditions imposed. Variations in the symmetry of plate motions generate strongly asymmetric basin floor deformation and alter the position of the depocenter(s) of the basin as well as the location and number of intra-basin horst structures. The addition of a second high-level polymer layer serves to localize intra-basin tectonic subsidence even further along cross-basin fault systems.

To date, most of the analysis of model results has been conducted using digital photographic images of the models - animating those images and generating 3D block diagrams illustrating the internal geometries of the pull-apart basins. Animations of the plan-view evolution of the models and cross-sectional geometries are presented in this talk. Current work includes the generation of 3D surfaces of various marker horizons within the basin allowing for down-section analysis of individual structures within the basin and specifically detailed analysis of the CBFZ within the various models. In addition, preliminary views of surface laser scanning techniques will be presented. This new technique allows the rapid acquisition of an 8 x 10^6 data cluster in 120 sec (Figure 9). The non-destructive nature of this technique and the rapid scanning times will allow sequential laser scanning of selected models during complete model runs. The data will be used to generate digital fly-through views, DEM's and surface analysis of the developing structure. Future work will also include 4D analyses of pull-apart basin development. Models will be "frozen" at various finite displacements in order to generate 3D models of the progressive development of transtensional pull-apart basins and apply these results to the Coso Field.

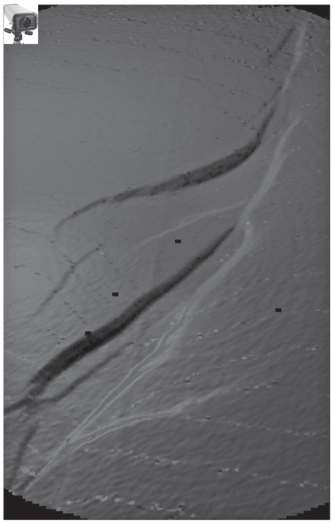

Figure 9. Output from a preliminary run using a surface laser-scanner to acquire topographic data. The scanner generates 8 x 106 data clusters in approximately 60 seconds and thus is ideal for generating sequential surface analyses of the developing pull-apart basin.

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