

APPENDIX 2: STRATIGRAPHIC SEQUENCES OF THE KINGS RIVER ALLUVIAL FAN FORMED IN RESPONSE TO SIERRA NEVADA GLACIAL CYCLICITY

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INTRODUCTION

Pleistocene glaciations in the Sierra Nevada produced significant amounts of sediment, much of which was deposited on alluvial fans and in basinal lacustrine or axial fluvial systems in the San Joaquin Valley. Cycles of high aggradation during periods of glaciation and low aggradation or erosion during interglacial periods have long been recognized from soil mapping (e.g., Janda, 1966; Arkley, 1962; Marchand, 1977; Marchand and Allwardt, 1981; Huntington, 1971, 1980; Harden, 1987) and subsurface analysis (Lettis, 1982, 1988; Atwater et al 1986).

Recently, Weissmann et al. (2002a) recognized stratigraphic sequences related to Pleistocene glaciations in the Kings River alluvial fan, located south of Fresno, California. In this work, they proposed a sequence stratigraphic conceptual model for deposition in large, stream-dominated alluvial fans (fluvial fans?) of the eastern San Joaquin Valley. The significance of the sequence stratigraphic model is that it provides a framework for regional- and local-scale analysis of groundwater flow and solute transport (e.g., Weissmann et al, 2002b, in press).

This paper outlines the alluvial fan sequence stratigraphic conceptual model and identifies stratigraphic sequences in the Kings River alluvial fan. Applications of this conceptual model as a framework for geostatistical modeling and in groundwater studies are beyond the scope of this paper, however details on such applications can be found in Weissmann and Fogg (1999) and Weissmann et al. (1999, 2002b, in press).

BACKGROUND

The advancement of concepts related to sequence stratigraphy has revolutionized geoscientist's views of stratigraphic development. Sequence stratigraphy provides a framework for prediction of facies distributions, enhancing our ability to predict and model subsurface fluid flow (e.g., petroleum and groundwater). In this approach, the stratigraphic section is divided into chronostratigraphic sequences, where a sequence is defined as "... a relatively conformable succession of genetically related strata bounded at its top and base by unconformities, or their correlative conformities" (Mitchum, 1977, p. 210). Although most applications of sequence stratigraphy have focused on marine or near shore settings, sequence stratigraphic concepts can likely lead to improved predictive modeling of facies in continental settings (Shanley and McCabe, 1994; Weissmann and Fogg, 1999; Weissmann et al., 2002a, 2002b).

Controls on sequence development in fluvial depositional systems, however, differ from those of marine depositional systems. Accommodation space, or space available for

sediment accumulation, in marine systems is primarily defined by relative sea level (controlled by eustatic sea level and local tectonics). In fluvial systems, Blum and Törnqvist (2000) suggest that accommodation should be viewed as a combination of accumulation space and preservation space. Accumulation space is controlled by variability in sediment supply and discharge, where the balance between these controlling factors determines whether a fluvial system is in aggradation, degradation, or at grade. Positive accumulation space exists when relatively long-term fluvial aggradation occurs at a site, while negative accumulation space exists in areas of degradation.

On alluvial fans, the intersection point separates regions on the fan that experience positive accumulation space from regions that experience negative accumulation space (Weissmann et al., 2002a). Above the intersection point, the alluvial fan river is held within an incised valley, thus indicating degradation and negative accumulation space. Below the intersection point, a depositional lobe exists where aggradation is occurring, thus indicating the presence of positive accumulation space. During periods of relatively high accumulation space, the intersection point lies at a position near the fan apex, with open-fan deposition occurring across most of the alluvial fan surface. During periods of low accumulation space, the intersection point shifts to a relatively distal position, the river is held in an incised valley, and the upper to mid-fan areas are exposed to soil development, erosion, and/or eolian reworking. These soils and the bases of incised valleys developed during the low accumulation space times mark the unconformities that eventually form the alluvial fan sequence boundaries.

Preservation space in a fluvial system is produced "... when subsidence lowers these deposits below possible depths of incision and removal" (Blum and Törnqvist, 2000, p. 20). Cycles in accumulation space form the stratigraphic sequences in a fluvial system, while production of preservation space allows the sequences to be preserved in the stratigraphic record.

SEQUENCE DEVELOPMENT ON ALLUVIAL FANS

Sequences on the Kings River alluvial fan were formed in response to glacial cyclicity in the Sierra Nevada (Figure 2-1). Development of sequence boundaries began on the Kings River alluvial fan at the end of glacial periods and the beginning of interglacial periods, when fan incision and a basinward shift in the fan intersection point occurred due to declines in the sediment supply to discharge ratio in the Kings River. This fan incision created an incised valley in the middle and upper portions of the fan. Throughout the interglacial period, deposition was confined to the distal portions of the fan while the upper alluvial fan was exposed to erosion, soil development, or modification by eolian processes. The base of the incised valley and the soils formed during the interglacial periods mark the sequence boundaries on the Kings River alluvial fan.

Rapid aggradation (e.g., accumulation space gain) occurred in response to higher sediment supply during the glacial events (Lettis, 1982, 1988; Weissmann et al., 2002a). Though discharge also increased significantly, the large sediment volume released from glaciers was sufficient to cause this aggradational event. Initially, the incised valley filled with a fining-upward succession of relatively coarse-grained channel and overbank deposits. Continued deposition due to high sediment supply to discharge ratios eventually filled the incised valley. Upon filling of the incised valley, the intersection point stabilized near the fan apex, leading to relatively unconfined deposition across the entire alluvial fan surface, or

open-fan deposition. These open-fan deposits consist of a mix of discrete coarse-grained, channel-fill deposits within fine-grained, silt-dominated overbank deposits. Sediments in the middle to upper portions of the Kings River alluvial fan are predominantly open-fan deposits. The end of glaciation led to repetition of this stratigraphic cycle with subsequent decrease in the sediment supply to discharge ratio (e.g., accumulation space loss), fan incision, basinward shift in deposition, and soil development on the upper alluvial fan.

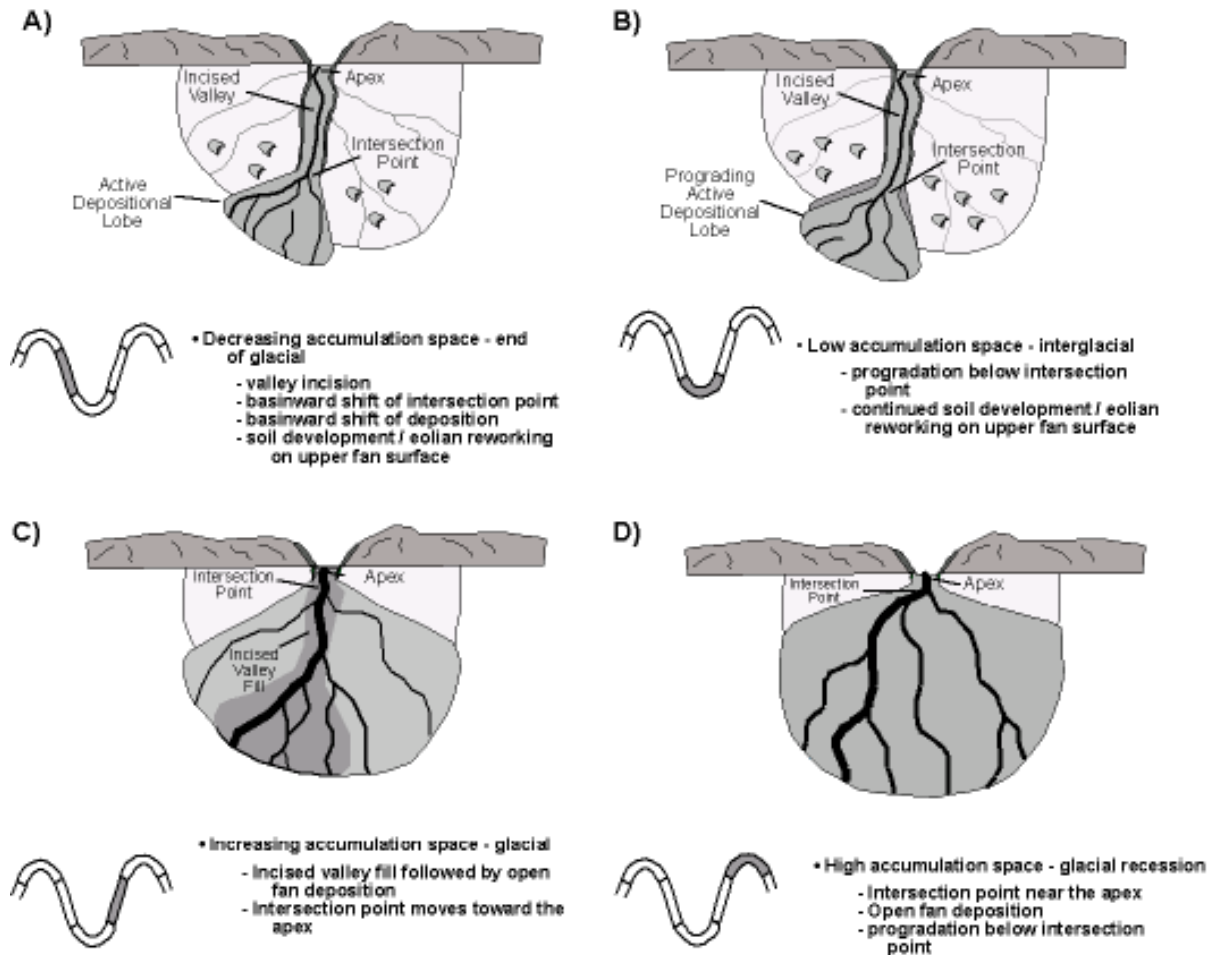


Figure 2-1. Sequence cycles on a stream-dominated alluvial fan. Darker shading indicates active areas of the alluvial fan. A) Decrease in accumulation space, B) Low accumulation space, C) Increase in accumulation space, D) High accumulation space. From Weissmann et al., 2002a.

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Methods and Data Sources

Several data sources provide evidence supporting this stratigraphic model for the Kings River alluvial fan. Excellent soil series maps, compiled and interpreted by Huntington (1971, 1980), allowed for geomorphic assessment of sequence distributions and facies trends. Subsurface analysis of the fan stratigraphy was based on core from seven stratigraphic test wells (Burow et al, 1997; Weissmann, 1999; Weissmann et al., 2002a), from lithologic descriptions from hundreds of driller's well logs, and from approximately 120 km of ground penetrating radar surveys (Bennett et al., 2002). Anyone who has used driller's well log data

understands the high uncertainty involved in interpreting these data, however, we found that drillers that used cable tool drilling methods were relatively accurate in their lithologic descriptions. Recent ground penetrating radar data collection provides information that shows the lateral distribution and continuity of the shallowest paleosol on the Kings River alluvial fan (Bennett et al, 2002). The subsurface data were compiled into cross sections, and sequence geometries were determined from these cross sections. This stratigraphic framework was used for detailed geostatistical modeling of facies distributions (Weissmann et al, 1999; Weissmann and Fogg, 1999), which was in-turn applied in groundwater modeling (Weissmann et al., 2002b, in press).

Observations and Stratigraphy

The modern interglacial topography of the Kings River alluvial fan shows that the Kings River is currently held in a 3 meter deep incised valley (Figure 2-2). The modern intersection point is located in a distal position, approximately 2 km south of Kingsburg. The valley is sufficiently deep to contain flooding of any magnitude from the current climatic regime, therefore, the upper fan surface no longer receives sediment (except for minimal eolian deposition) and was exposed to soil development prior to intensive reworking through modern agriculture. Below the intersection point, aggradation on a depositional lobe (Laguna de Tache) occurred until the construction of Pine Flat Reservoir, located in the Sierra Nevada foothills on the Kings River.

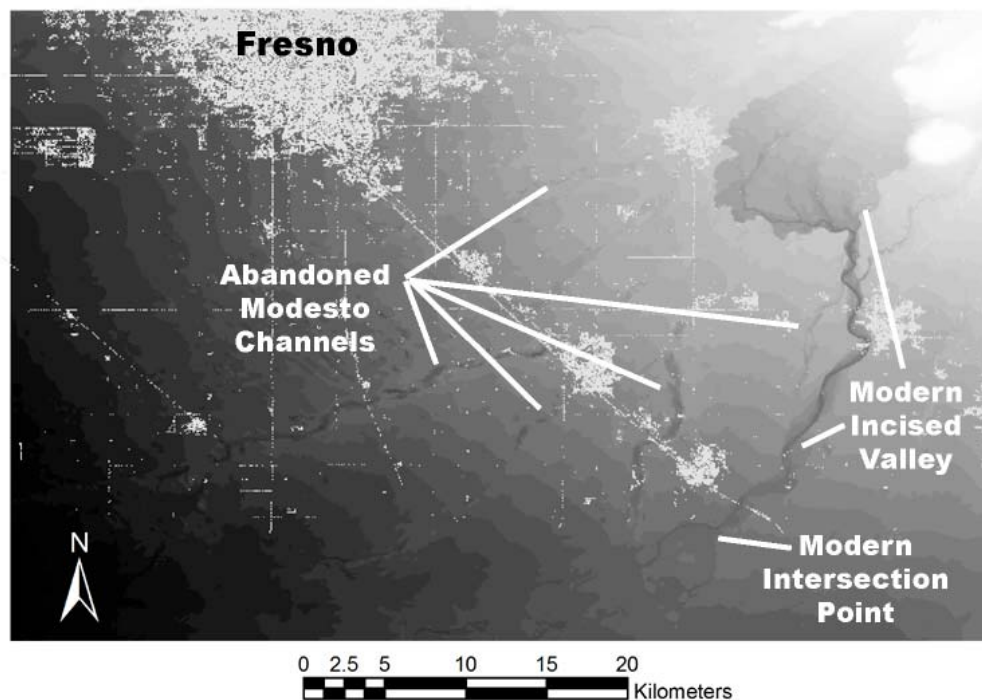


Figure 2-2. A digital elevation model for the upper Kings River alluvial fan (higher elevations shown as lighter shades) showing the modern incised valley and Modesto abandoned channels.

Also apparent on topographic maps, aerial photographs, satellite images, and soil surveys are a series of abandoned channels on the exposed upper fan surface that radiate outward from an old intersection point located near the fan apex approximately 4.5 km east of Sanger (Figure 2-2; Huntington, 1971, 1980; Weissmann et al., 2002a). Soil development and surrounding lithologies (e.g., relatively ‘fresh’ silt that appears to be similar to glacial flour) indicate these channels were active during the most recent glacial event (Huntington, 1971; 1980). Thus, open fan deposition appears to have occurred on the upper fan surface during glacial events. Regional correlation puts these most recent deposits in the Modesto Formation (Figure 2-3). The widths of these channels are consistent with significantly greater discharge in the Kings River expected during glacial episodes, however the thick succession of fan deposits indicates that the sediment load was sufficient to cause aggradation.

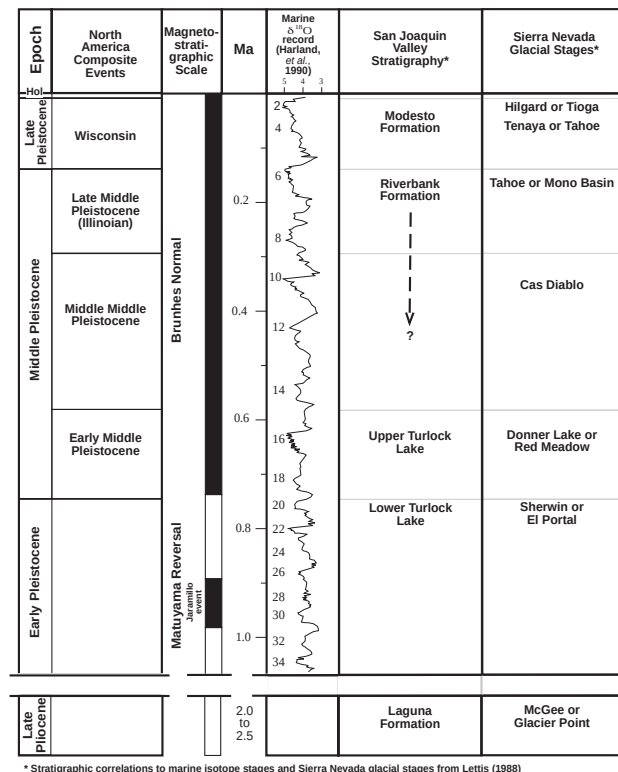


Figure 2-3. The stratigraphic column for the Kings River alluvial fan (based on Marchand and Allwardt, 1981; Harden, 1987; Lettis, 1988). Each stratigraphic unit consists primarily of stream-dominated alluvial fan deposits (From Weissmann et al., 2002a).

Soil morphologies can also be used to identify older, open fan deposits (e.g., Riverbank Formation, Turlock Lake Formation; Huntington, 1971, 1980). Relatively long-term exposure of these deposits has led to development of duripans. Because these units were deposited near the fan apex, the intersection point during these past glaciations must have also been near the apex, indicating that accumulation space was broadly available.

The hard B-horizon of the Riverbank Formation soils can be traced across the shallow subsurface on much of the Kings River alluvial fan. Soil surveys (Figure 2-4), extensive ground penetrating radar surveys (Bennett et al., 2002), and well log correlation (Figure 2-5) indicate that this soil is buried under a relatively thin veneer of Modesto Formation deposits.

This soil (paleosol) forms one of the sequence boundaries on the Kings River alluvial fan, separating the Riverbank Formation from the Modesto Formation.

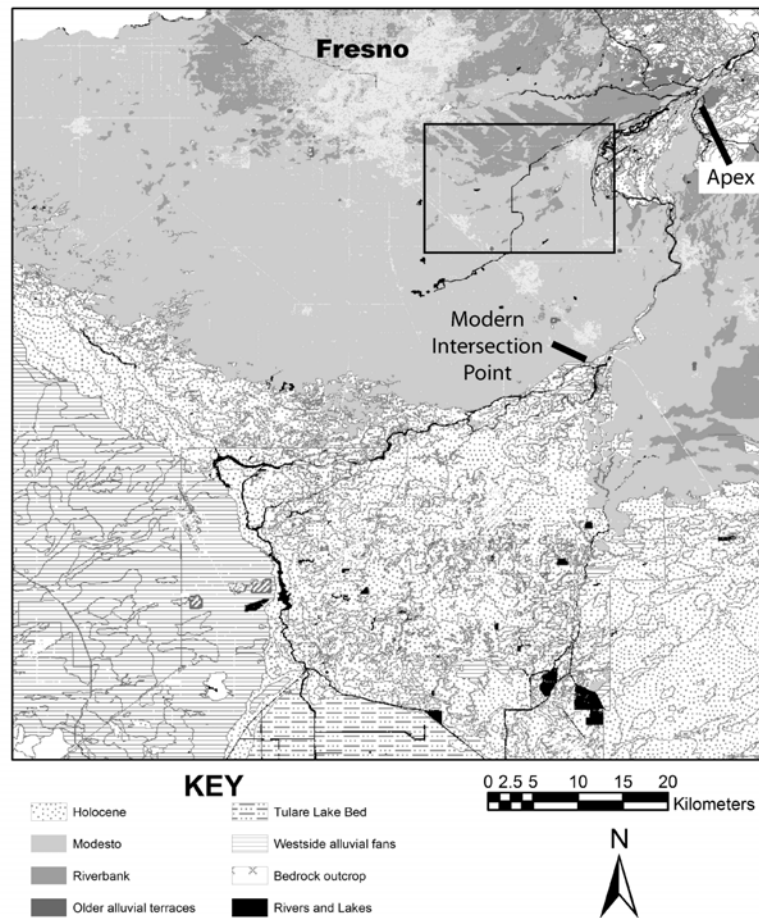


Figure 2-4. Interpreted soil survey of the Kings River alluvial fan showing the surface distribution of sequences (modified from Huntington, 1971).

The Riverbank soil, along with two paleosols that were correlated to the Turlock Lake, can be traced into the subsurface using driller's well logs and core (Figure 2-5). These soils appear as reddish clay-rich units. In the case of the paleosols that cap the Riverbank and upper Turlock Lake units, the paleosols appear as beds that dip at low angle into the basin, 'outcropping' close to areas mapped by Huntington (1971) for each of these units.

In the conceptual model, we propose that an incised valley must exist on the fan during interglacial periods in order to keep aggradation from occurring across the upper fan, thus allowing for soil development on the sequence bounding surfaces. The most recent incised valley (developed during the interglacial period between the Modesto and Riverbank times) was identified south of Sanger based on soil character and subsurface facies indications from driller's logs. The soil surveys indicate a sharp break in the Riverbank soils along a line south of Sanger (Figure 2-6). Additionally, driller's log data indicated the presence of cobbles at a depth of approximately 30 meters. These logs also lacked evidence for expected paleosols (capping the Riverbank and Upper Turlock Lake units) above this gravel unit.

Subsequent drilling and core collection showed that sediments in this area were significantly coarser grained than surrounding open fan deposits, consisting of an 8-m thick basal cobble unit that is overlain by a fining upward succession of very coarse to medium sand (Weissmann et al., 2002a, *in press*). Some overbank silts are present, but in significantly lower proportions relative to surrounding open fan deposits (Weissmann et al., 2002a, 2002b).

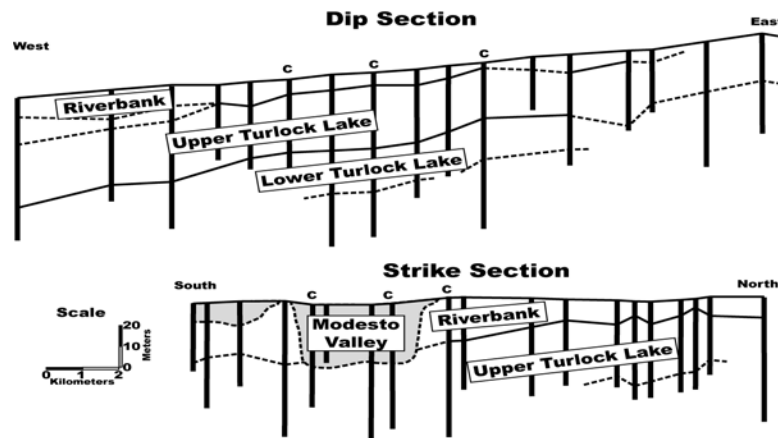


Figure 2-5. Cross sections through the Kings River alluvial fan. Correlations mark the paleosol sequence boundary markers. Wells labeled with a “C” indicate core collected. Modified from Weissmann et al., 2002a, *in press*.

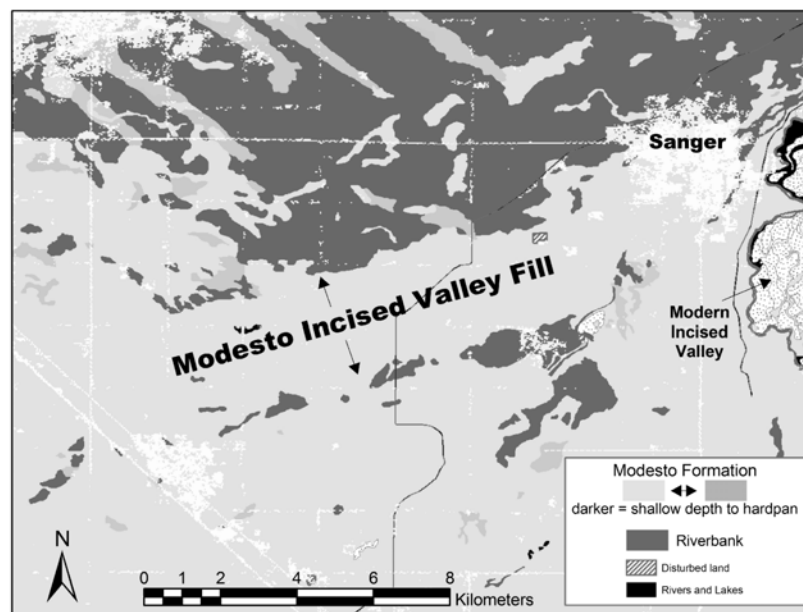


Figure 2-6. Detail of the soil survey around the incised valley fill. The incised valley fill is surrounded by Riverbank Formation outcrops (modified from Weissmann et al., 2002a).

Correlation of paleosols and the incised valley fill allow development of a 3-D stratigraphic framework that can be used for prediction of facies distributions in the alluvial fan (Figure 2-7). Models that have been developed in this framework honor the differences

between open fan and incised valley fill deposits, thus providing a reasonable characterization of the complex alluvial fan aquifer (Weissmann and Fogg, 1999; Weissmann et al., 1999, in press).

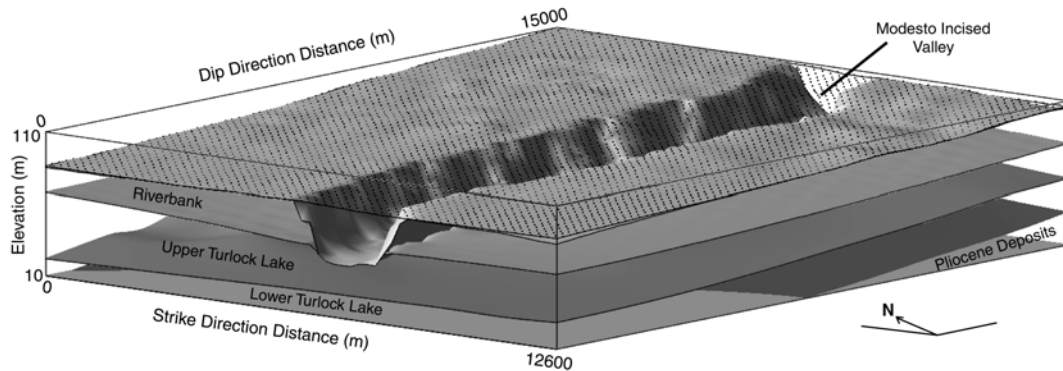


Figure 2-7. A block diagram showing the sequence surfaces in the upper Kings River alluvial fan as defined by paleosol correlation and the Modesto incised valley fill geometry (modified from Weissmann et al., *in press*).

CONCLUDING REMARKS

Stratigraphic sequences on the Kings River alluvial fan, related to past glacial cyclicity in the Sierra Nevada, contain a predictable distribution of facies related to processes that were active at different stages of glacial outwash. Sequences observed in the middle to upper fan are bounded by relatively mature paleosols. These sequences formed in response to changes in sediment supply and discharge, and consist of both open fan and incised valley fill deposits. Open fan deposits, consisting of relatively wide and straight channel sands and gravels surrounded by overbank silt, dominate the upper to middle fan stratigraphic section. Incised valley fill deposits consist of a relatively coarse-grained, fining upward succession. In standard sequence stratigraphic terminology, the open fan and incised valley fill units might represent systems tracts in the sequences.

Importantly, the sequence stratigraphic model allows for prediction of facies distributions on the fan. For instance, we expect to find an incised valley fill unit associated with each sequence bounding paleosol. Preliminary work on the Tuolumne alluvial fan, located in Modesto, California, indicates the presence of a large incised valley fill deposit located below the city. The sequence stratigraphic model allowed identification of this unit and offers information about the geometry of the coarse grained deposit.

The importance of identifying the incised valley fill and other facies patterns in these alluvial fans was shown by Weissmann et al. (*in press*). In this work, the authors modeled the influence of the coarse-grained incised valley fill on regional groundwater recharge and flow. Because this unit is coarser than surrounding deposits, it essentially acts as a 'conduit' for both groundwater recharge and contaminant migration into deeper and adjacent aquifer units. We expect future work to continue building our understanding of the stratigraphic influence on groundwater flow and contaminant transport as well as continued development of models for the Quaternary San Joaquin Basin fill.

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