Integrated Stratigraphic and Hydrogeologic Aquifer Analysis: Toward Improved Multi-scale Characterization of Alluvial Aquifer Systems

PI: Gary Weissmann, University of New Mexico

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PROJECT SUMMARY

One of our primary goals as hydrogeologists is to accurately model and predict the transport and fate of contaminants in groundwater systems. This modeling effort is critical to ensure a clean and safe drinking water supply. To reach this goal, the geologic and hydrogeologic communities generally recognize the need for methods to produce detailed aquifer characterization through integrated geological and hydrological assessment, especially in highly heterogeneous aquifer systems such as stream-dominated alluvial fans. However, we must not only develop new approaches to accomplish this fusion of geology and hydrology, but we must also simultaneously produce examples of this integrated approach for undergraduate-level class activities so future practitioners and researchers will appreciate the importance of aquifer characterization.

To begin reaching these goals, the PI and colleagues previously developed a novel sequence stratigraphic approach to characterizing hydrofacies distributions on a stream-dominated alluvial fan system in the San Joaquin Valley of California, where sequences, bounded by mature paleosols, reflect cycles in accumulation space associated with changes in the sediment supply to discharge ratio during Pleistocene glacial cycles. This approach significantly enhanced detailed aquifer simulation and groundwater modeling efforts in that study area. However, several questions resulted from this previous work that will guide this proposed research project, including: 1) do sequences exist in other alluvial fan systems; 2) are recognizable systems tracts present on other fans; 3) do sequences, bounded by clay-rich mature paleosols, compartmentalize groundwater flow into hydrostratigraphic units; and 4) can sequence stratigraphy provide a framework for improved groundwater modeling on other alluvial fan systems.

Through sedimentologic and paleopedologic analysis of extensive core and hydraulic test data at the Lawrence Livermore National Laboratory (LLNL), a site with extensive core, geophysical well log, and 3D hydrologic test data, we intend to test hypotheses that are formed from these questions. Preliminary work at the LLNL site indicates that mature paleosols may bound previously defined hydrostratigraphic units, thus indicating that paleosol bounded sequences exist here and that sequence geometry strongly influences aquifer hydrodynamics. Through this work, we will (1) describe about 6000 meters of previously collected continuous core, (2) assess paleosol morphology and chemistry within the section, (3) construct and model the 3-D stratigraphy at the LLNL site, and (4) model the multi-scale facies distributions, groundwater flow, and contaminant transport within this complex aquifer system. These models will be tested against aquifer test and contaminant concentration data. Results from this detailed analysis may guide future methods for conducting analyses of other stream-dominated alluvial fan aquifer systems, an extremely important aquifer type in the western US.

A major objective of this work is to involve many undergraduate researchers in various aspects of the project. To accomplish this goal, several undergraduate researchers will be directly involved in daily research activities. Additionally, aspects of this research will be incorporated into classroom activities, where students in a class that focuses on the geology of aquifers and petroleum reservoirs will assess core, construct the 3-D stratigraphic framework at a small site, and model the heterogeneity at the site. This will not only involve more students in the research project, but will provide multiple 'realizations' of the stratigraphic character for assessment of uncertainty in the characterization results. An additional benefit of this research is development of appropriate classroom exercises that incorporate geologic and hydrologic analysis. The 3D hydrologic data, collected from discrete intervals in the LLNL aquifer system, along with core resources, provide a unique resource to examine aquifer response to stratigraphic character. Few examples that are appropriate for direct use as classroom activities at the undergraduate-level are available in the literature, thus publication of these results as level-appropriate exercises will broaden the pedagogical impact of this research.

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INTEGRATED STRATIGRAPHIC AND HYDROGEOLOGIC AQUIFER ANALYSIS: TOWARD IMPROVED MULTI-SCALE CHARACTERIZATION OF ALLUVIAL AQUIFER SYSTEMS

INTRODUCTION

Alluvial fans comprise many important aquifer systems in the western U.S. and around the world, yet, with few exceptions (e.g., Muto, 1987, 1988; Wright and Alonso Zarza, 1990; Alonso Zarza *et al.*, 1998; Weissmann *et al., in press*), detailed stratigraphic characterizations of these deposits remain absent in the geologic and hydrogeologic literature. Such geologically-based aquifer characterizations, however, are critical for development of accurate contaminant fate and transport models used for evaluation of remediation strategy effectiveness at contaminated sites (Fogg, 1986; Fraser and Davis, 1998). Successful application of sequence stratigraphic concepts to aid definition of petroleum reservoir character (e.g., Vail *et al.*, 1977; Posamentier *et al.*, 1988; Posamentier and Vail, 1988; VanWagoner *et al.*, 1990; Sarg, 2001) led the PI and colleagues to develop sequence stratigraphic concepts on the Kings River Alluvial Fan aquifer system (Weissmann *et al., in press*). This new stratigraphic model provided a framework for modeling multi-scale facies distributions (Weissmann and Fogg, 1999) thus providing unprecedented detail of heterogeneous aquifer properties for groundwater flow and contaminant transport models. This work not only provided a novel approach to characterizing alluvial fan deposits, but it also provided a new method to integrate geologic and hydrologic data at a complex, heterogeneous site. Further tests of this integrated alluvial fan sequence stratigraphic/hydrogeologic approach to aquifer characterization, however, must be conducted in order to generalize the approach to broader application on other alluvial fan systems.

A unique opportunity exists to study and improve this integrated approach for constructing multi-scale models of alluvial aquifer heterogeneity at the Lawrence Livermore National Laboratory (LLNL), located in Livermore, California. Several thousand meters of continuous core and high quality geophysical well logs from over 700 wells within the 2.6-km^2 LLNL property provide a superb data set from which to assess the complex alluvial fan stratigraphy of the site. Surprisingly, most of this extraordinary core data set has never been assessed in detail for stratigraphic character of the alluvial fan system. In addition to the extensive core resource, data from multiple aquifer tests along with contaminant distribution measurements through time exist. Importantly, these hydrologic data were collected over small-screened intervals (e.g. 2-meters), thus offering a three-dimensional hydrologic data set that can be directly compared to the site stratigraphy. This outstanding data set not only provides strong potential for research, but students involved in this work also gain additional benefit from seeing their research applied in a real-world setting. Though funding for a pilot project was available over the past year from LLNL, future funding opportunities no longer exist due to significant budget cuts.

Through this proposal, my students and I intend to continue development of sequence stratigraphic concepts for alluvial fans through testing and refining the approach on the LLNL aquifer system. Additionally, through integration of these stratigraphic models with hydrogeologic modeling, we will develop a better understanding of contaminant transport in this complex aquifer type. This work will include description and analysis of core, detailed micromorphologic analysis of pedogenically modified successions from selected core, calibration and analysis of the geophysical well log data, definition of sequence geometries and systems tracts within the stratigraphic section, geostatistical modeling within the stratigraphic framework, and groundwater flow and contaminant transport simulation using this modeled heterogeneity. Groundwater modeling aspects of this research will be conducted in collaboration with LLNL hydrogeologists. Comparison of contaminant transport and groundwater flow results to aquifer test and tracer test data will provide validation of the integrated stratigraphic/hydrogeologic models. Importantly, aspects of this research can be completed as classroom projects, thus offering students at both the graduate and upper division undergraduate level the opportunity to be directly involved in this research. Other aspects of the research are conducive for designed classroom exercises, and will be developed and published in this manner.

This project forms a significant cornerstone of my research and teaching program. My professional research goals focus on understanding how alluvial basins fill (e.g., what internal and external factors produce the stratigraphy that we see in these deposits), what facies distributions and geometries develop within the alluvial basin fill and how can we best model these facies, and what influence does this stratigraphic character have on groundwater flow and the distribution and movement of contaminants within an aquifer system. This proposed project, along with another project that focuses on fan variability around the San Joaquin Basin, are currently being used to address these research questions and will form a strong basis for future work in basin analysis approaches to hydrostratigraphic characterization. In my teaching, I strive to offer students an integrated approach to aquifer and basin assessment through participatory classroom exercises and projects. I hope my students will develop an intuition about stratigraphic controls on the hydrodynamics of aquifer (or petroleum) systems, thus positioning them to play a leading role in future research or in the workplace. Additionally, by sharing collaborative learning exercises that incorporate geologic and hydrologic aspects into aquifer characterization, we can bring these new concepts to a broader audience of students and professionals.

Aligned with my professional goals, Michigan State University is a research intensive university with a strong commitment to student learning. Thus, undergraduate involvement in research is strongly encouraged. Additionally, the Department of Geological Sciences assigns high value to quality courses that include active and cooperative exercises. Thus, the research and educational goals of this proposal fit well with the institutional goals of MSU and the Department.

CONCEPTUAL FRAMEWORK AND SIGNIFICANCE

An overarching hypothesis that guides my research program is that geologic facies variability controls aquifer heterogeneity, and thus, contaminant fate and transport. Therefore, by improving our ability to characterize and predict facies distributions, we can significantly enhance groundwater flow and contaminant transport modeling results. My current approach is to develop sequence stratigraphic models for alluvial fan deposits in order to predict the facies character on different portions of the fan, thus providing a framework for modeling facies distributions. In the Kings River alluvial fan system, we have been able to use this approach to model environmental tracer concentrations that reasonably match measured concentrations (Weissmann *et al.*, 2000; Zhang *et al.*, 2000). Though this sequence stratigraphic approach is proving to be successful at the Kings River Alluvial Fan study site, many questions arose about broader applicability of this approach to other alluvial fan systems. Specifically,

- Do paleosol-bounded sequences exist in other stream-dominated alluvial fan deposits, even when these fans developed in basins outside direct influence of glacial outwash cycles?
- Systems tracts in the Kings River Alluvial Fan were recognizable, in part, due to the distinct sediment nature produced by glacial outwash. Are similar systems tracts apparent in other alluvial fans?
- Can the paleosol morphology in this sequence stratigraphic framework be used to assess autogenic and allogenic controls responsible for producing the observed stratigraphic character?
- Do these sequence bounding paleosols compartmentalize groundwater flow, effectively separating the aquifer into distinct but somewhat connected hydrostratigraphic units?
- Can sequence stratigraphy provide a general framework to improve hydrogeologic models on other alluvial fan systems?

Answers to these questions go the heart of both basic and applied problems in stratigraphy, basin analysis, and hydrogeology. The basic research problem is that alluvial fan stratigraphy is poorly understood and difficult to characterize. Most published work, in fact, shows this stratigraphy as chaotic (e.g., DeCelles *et al.*, 1991; Kelly and Olsen, 1993). The sequence stratigraphic approach to fan characterization, however, may offer a means to evaluate and predict internal facies distributions within an alluvial fan (Weissmann, 1999; Weissmann *et al.*, *in press*). The applied research problem is that hydrogeologists must predict subsurface contaminant movement and remediation strategy effectiveness, thus accurate models of aquifer heterogeneity are needed. Additionally, newly trained hydrogeologists (e.g., our students) should be able to understand patterns of heterogeneity and incorporate them into their groundwater models whenever possible, therefore applied examples of such integration are needed.

The significance of this research is four-fold. First, it will test and refine the sequence stratigraphic model of Weissmann *et al.* (*in press*), thus creating order in our understanding of heterogeneity in many alluvial fan systems that are now viewed as chaotic. Second, this research will assess components of the stratigraphic system to determine their influence and relative importance in controlling the overall hydrogeologic character of an aquifer system. Third, the research will provide a large step forward in our ability to characterize and model groundwater flow and contaminant transport in alluvial basin fill deposits. Finally, this research will provide several opportunities for students to be involved in a research program, both in and out of the classroom, and to gain experience working with complex geologic and hydrologic data sets.

RELATED AND PREVIOUS WORK

Alluvial Fan Characterizations and Sequence Stratigraphy

Most descriptions of alluvial fan stratigraphy lack information about the three-dimensional distribution of facies. Many studies concentrate on the fan geomorphology in attempts to develop facies models for the alluvial fan systems (e.g., Walker and James, 1992; Stanistreet and McCarthy, 1993), however these models shed minimal insight into the regional subsurface distribution of sediment. Other descriptions of alluvial fans and similar fluvial deposits may develop three-dimensional concepts based upon combinations of two-dimensional cross-sections and fence diagrams (e.g., Blair *et al.*, 1991; Hirst, 1991), but the facies distributions between the cross-sections are rarely estimated. Additionally, thick packages of alluvial fan sediments tend to be drawn as massive and chaotic units, with no stratigraphic markers dividing the unit into successions deposited under similar conditions.

Recent studies, however, have indicated that a stratigraphic framework does exist in alluvial fan systems. For example, Wright and Alonso Zarza (1990) and Alonso Zarza *et al.* (1998) presented a paleosol-based stratigraphy for alluvial fans in Spain, where paleosols that were formed during fan incision mark major unconformities produced by allogenic controls of climate or tectonic change. These paleosols display greater maturity and lateral continuity than paleosols formed in response to autogenic shifts of depocenters across the fan. Additionally, Muto (1987; 1988) presented a sequence stratigraphic model of alluvial fans in Japan. In these fans, sea level change produced cycles in aggradation and erosion, thus forming sequence boundaries marked by the base of incised valleys and interfluve paleosols. Muto’s approach indicates that sequence stratigraphic concepts can successfully be applied to alluvial fan systems. However the mechanisms controlling sequence development in fully continental settings (i.e., not significantly influenced by sea or lake level changes) remain unclear since sea (or lake) level change only significantly affects the low gradient reaches of rivers near the shoreline (Leopold and Bull, 1979; Miall, 1991; Blum, 1993; Shanley and McCabe, 1994; Ethridge *et al.*, 1998). Sequences have also been recognized in other, fully continental successions of fluvial basin fill deposits (Hanneman and Wideman, 1991; Hanneman *et al.*, 1994), though processes responsible for their development remain unclear.

Weissmann (1999), Weissmann and Fogg (1999), and Weissmann *et al.* (*in press*) recently developed and applied a sequence stratigraphic model for the Kings River Alluvial Fan, a stream-dominated alluvial fan located southeast of Fresno, California. In this model, fan sequences reflect changes in ‘accumulation space’ (after Blum and Törnqvist, 2000) associated with changes in the ratio of sediment supply to discharge during Pleistocene glacial cycles in the Sierra Nevada Mountains (Figure 1). San Joaquin Basin subsidence created preservation space for these sequences. At the end of glacial periods and the beginning of interglacial periods, declines in sediment supply to discharge ratios led to fan incision, a basinward shift in the fan intersection point, and loss of accumulation space. In mid- and upper-fan settings, incised valleys and laterally extensive, moderately mature paleosols formed, marking the unconformable base of the depositional sequence. Throughout the interglacial period, relatively low accumulation space existed and deposition was confined to the distal portions of the fan. Rapid aggradation, and thus rapid accumulation space increase, in response to higher sediment supply during the next glacial event, initially filled the incised valley with a fining-upward succession of relatively coarse-grained channel and overbank deposits. Upon filling of the incised valley, the intersection point stabilized near the fan apex. This led to unconfined open fan deposition, indicating that widespread accumulation space was available across most of the fan surface. These high accumulation space units consist of fluvial deposits from multiple, large glacial outwash channels that radiated outward from the proximally located intersection point. The end of glaciation brought repetition of this stratigraphic cycle with subsequent loss of accumulation space and basinward shift in deposition.

Laterally extensive, mature paleosols, recognized in driller's logs, core, and geophysical surveys, mark sequence boundaries (Figure 2). The distribution and form of paleosols observed in the Kings River Alluvial Fan system appear to match those describe by Wright and Alonso Zarza (1990) and Alonso Zarza *et al.* (1998) in that paleosols within the sequences display evidence of lesser development than those formed on sequence boundaries during fan incision.

The sequences also consist of identifiable systems tracts that appear to contain predictable facies assemblages (Weissmann, 1999; Weissmann *et al.*, *in press*). Lower accumulation space sediments (systems tracts) from the interglacial periods were deposited by smaller rivers and consist of less silt than those of high accumulation space deposits. Rising accumulation space deposits (systems tracts), represented by incised valley fill sediments, consist of very coarse-grained sediment that also contains significant fresh silt (glacial flour). Finally, high accumulation space units (systems tracts) were deposited by relatively large rivers and contain significant fresh silt (glacial flour) in relatively thick floodplain successions.

Though direct connection to glaciated regions does not exist for most stream-dominated alluvial fan systems, Bull (1991) presented evidence of aggradational cyclicity related to Pleistocene climate change in alluvial deposits of the Southwestern United States. Bull (1991) hypothesized that the change from a wetter glacial period to dryer interglacial caused significant loss of vegetation on regional hillslopes, thus resulting in increased sediment supply and aggradation of alluvial systems. Koltermann and Gorelick (1996) also recognized a similar phenomenon on alluvial fans in the San Francisco Bay area, and Mack *et al.* (1994) identified cyclicity in fluvial sedimentary deposits related to Pleistocene climate change in the Rio Grande Valley of New Mexico. Therefore, a climatic signature could produce aggradation/erosion cyclicity in settings not directly connected to glaciation.

Testing of this hypothesis, however, may be difficult (Dorn 1996), since tectonic variability or high intensity storm events may also be responsible for varying accumulation and erosion rates. Additionally, other workers (e.g., Schumm, *et al.*, 1987; DeCelles *et al.,* 1991; Fraser and DeCelles, 1992) presented autocyclic mechanisms that could be responsible for producing sedimentary cyclicity. Paleosol and facies character within sequences may help resolve which of these mechanisms is dominant. For instance, if climatic cycles produced the sequences, we would expect the number of sequences to match the number of glacial/interglacial cycles (assuming that the incised valleys filled during each accumulation space rise). Additionally, relative maturity of paleosols developed during interglacial periods, shown by degree of weathering, should correspond to the reported intensity and length of interglacial periods as indicated by the marine isotope and IRD record (e.g., Imbrie, *et al.*, 1993; Venz, *et al.*, 1999). Autogenic mechanisms would presumably create a stratigraphy that appears more random, as would tectonic mechanisms. However, one would expect autogenic processes to produce a greater number of sequences as accumulation space fills since forcing mechanisms (e.g., sediment supply and discharge) would remain chaotic but relatively constant through time. Additionally, Wright and Alonso Zarza (1990) and Alonso Zarza *et al.* (1998) suggest that soils produced by autogenic processes would display less lateral continuity than those produced by allogenic processes. Whether sequences develop due to tectonic, climatic, or autogenic factors, the distribution of sequences defined by this approach provides a critical framework within which detailed aquifer characterization is possible.

Paleosol micromorphology and geochemical analysis

Key to understanding alluvial fan sequence development and geometry is interpreting paleosol distribution and development within the stratigraphic succession. Paleosols have been shown to be useful in interpreting paleoenvironment (Bown and Kraus, 1981; Kraus, 1987, 1996; Retallack, 1986; Mack *et al.*, 1993, 1994; Mack and James, 1994; McCarthy *et al.*, 1997a, 1997b, 1998). Paleosol interpretation within alluvial deposits, however, is complex because of the interaction of floodplain deposition, which is highly variable both spatially and temporally, and soil development (Kraus and Aslan, 1993, Kraus, 1996, McCarthy, 1998). Soils developed on floodplains may consist of multiple stacked pedogenic events, where lower portions of a soil developed on a thin flood deposit overprint buried soils formed during an earlier exposure period.

Detailed micromorphological analysis has been applied for reconstruction of pedogenic and depositional processes in complex modern soils and paleosols (Wilding and Flach, 1985; Bullock and Thompson, 1985; Bronger *et al.*, 1987; Feijtel, *et al.*, 1988; McCarthy *et al.* 1997a, 1997b, 1998). Micromorphological features observed in thin section, such as illuviated clay coats, carbonate form and distribution, root traces, and burrows, are related to processes responsible for producing them, which, in turn, are related to the paleoenvironment during pedogenic modification (Bronger *et al.,* 1987, 1994; Wilding and Flach, 1985; McCarthy *et al.* 1998). These features can be used to establish a sequence of geologic and pedogenic events (Courty and Fedoroff, 1985; Fedoroff *et al.*, 1990; McCarthy *et al.*, 1998). Importantly, this approach may provide evidence for changes in climate or deposition in a fluvial succession (McCarthy *et al.*, 1997a, 1997b, 1998).

Micromophologic analysis is strengthened by assessing relative chemical distributions within the succession (Maynard, 1992; McCarthy *et al.*, 1997a). Molar ratios of relatively inert geochemical indicators, such as Ti/Y, Ti/Zr, Zr/Y, and Al/Ti, have been used to detect lithologic discontinuities and, thus, to identify individual depositional units within the complex alluvial succession (Maynard, 1992; McCarthy et al. 1997a). This allows one to separate pedogenic affects from depositional layering. Additionally, Ti, Y, and Zr are found in minerals that are resistant to weathering and tend to accumulate as weathering progresses (McCarthy *et al.,* 1997a). Thus, ratios of mobile to these immobile elements (e.g., Fe/Ti; Al/Fe; Ca+Na/Ti) and the chemical index of alteration (CIA of Nesbitt and Young, 1982) can offer an indication of degree of weathering and relative soil maturity (Maynard, 1992; Feaks and Retallack, 1988; McCarthy *et al.,* 1997a).

Application of Transition Probability Geostatistics within the Sequence Stratigraphic Framework

Weissmann and Fogg (1999) applied transition probability geostatistics within the sequence stratigraphic framework to produce a multi-scale model of aquifer heterogeneity at the Kings River alluvial fan study site (Figure 3). Transition probability geostatistics, developed by Carle and Fogg (1996) and Carle (1997), provides a stochastic method to model the distribution of facies that allows introduction of conceptual geologic reasoning (Carle *et al.*, 1998; Weissmann *et al.,* 1999; Weissmann and Fogg, 1999). Incorporation of conceptual geologic information into the Markov chain models allows development of improved models in the typically undersampled, lateral directions (Eschard *et al.*, 1998; Weissmann *et al.*, 1999). However, a key assumption used in this and other geostatistical approaches is that of stationarity (e.g., statistics developed for the 3D Markov chain or variogram models are valid throughout the region the models are being applied). Stratigraphic character, however, often varies within a deposit, making this assumption tenuous.

Sequence stratigraphic concepts help us overcome this problem by dividing the stratigraphic succession into units that have similar properties (e.g., systems tracts within the sequences) (Weissmann and Fogg, 1999). By using the transition probability geostatistics within a sequence stratigraphic framework, realizations of the alluvial fan facies distributions are produced that account for multi-scale heterogeneity represented by spatially variable hydrofacies within the sequences, laterally extensive aquitard units at sequence boundaries, and spatially variable attributes that are unique to each sequence while preserving stationarity. In this approach, the distribution of large-scale features, such as sequence bounding paleosols, are modeled through a deterministic approach of well log correlation. Variability and erosional breaks within these paleosols are then modeled stochastically. Each sequence is modeled individually using transition probability geostatistics, thus avoiding cross-correlation between sediments of different sequences. These individual sequence and paleosol realizations are combined to produce a final stochastic model of aquifer heterogeneity (Figure 3) that honors the multi-scale nature of these complex deposits (Weissmann and Fogg, 1999). Production of multiple realizations allows an assessment of uncertainty of simulation results. Recent groundwater models using this geostatistical approach to defining hydrofacies distributions show improved matches to measured hydraulic and environmental tracer (chlorofluorocarbons) data (Weissmann *et al.*, 2000; Zhang *et al.*, 2000).

Previous Aquifer Studies at LLNL

The LLNL study site is located within the Livermore Valley, an east-west trending structural basin within the California Coast Ranges. History as a naval air base and national research facility has led to significant groundwater contamination, and, thus, listing on the Superfund National Priorities List in 1987. Offsite contamination has, thus far, been controlled, however the complexity of this alluvial aquifer system has been a hindrance to determining contaminant pathways and travel times for developing remediation strategies. Attempted remediation of multiple contaminant plumes at the site, consisting primarily of volatile organic compounds (VOCs), is currently underway.

The Livermore Valley is a complex and active synclinal structure (Carpenter *et al.*, 1984). It is bounded on the south by the Diablo Mountain Range and the Verona/Las Positas/Tesla fault system, on the east by the Greenville fault complex, on the north by Mount Diablo and associated uplifts, and to the west by the Calaveras fault system (Dibblee, 1981; Carpenter *et al.*, 1984). Movement on these faults is contemporaneous with deposition of the alluvial basin fill, as evidenced by uplifted and folded alluvial deposits of the Plio-Pleistocene Livermore Formation southeast of the study area (Carpenter *et al.,* 1984). Sediment is currently supplied to the LLNL alluvial fan complex via Arroyo Las Positas Creek to the east and Arroyo Seco Creek to the south. These creeks were probably responsible for basin deposition through the Pleistocene at the study site, however movement along faults may have shifted fan apexes through time (Carpenter *et al.,* 1984). Both creeks drain westward into the central portion of the basin, eventually joining Arroyo de Laguna Creek west of Pleasanton, which, in turn, discharges into the Alameda Creek and the San Francisco Bay about 40 km south of the study area (Carpenter *et al*., 1984). This distance, along with structural and bedrock control of the Alameda Creek drainage system, indicates that sea level change had no direct influence on Pleistocene stratigraphic character at the LLNL site. Fossil evidence indicates that basin fill forming the Upper Livermore Formation (the contaminated zone of interest) has been relatively continuous for the past 4-600,000 years (Carpenter *et al.*, 1984). Prior to this, lacustrine and fluvial sediments of the Lower Livermore Formation filled the basin.

Detailed hydrogeologic assessment of the upper Livermore Formation has been conducted by several workers (Blake *et al.*, 1995; Carle, 1996; Carle et al., 1998; Fogg *et al.*, 1998; Noyes *et al.*, *submitted*). Carle and Fogg (1996) first developed and applied the transition probability geostatistics approach to the southwest portion of the LLNL site in order to construct detailed characterizations of subsurface facies distributions. Groundwater modeling results based on these geostatistical realizations compared favorably to aquifer test results (Carle, 1996), however laterally extensive paleosols that exist at the site (as will be discussed later) were not recognized during this study. Instead, the alluvial fan succession was modeled as a massive, heterogeneous succession. Additionally, other facies distributions could be refined by further assessment of core data.

Recent work indicates that a hydrostratigraphic structure exists at the LLNL study site (Blake *et* *al.*, 1995; Noyes, *et al. submitted*) and that hydrodynamics differ between these hydrostratigraphic units (HSUs). Evaluation of plume concentrations and evidence (or lack of evidence) for hydraulic connection based on pumping test results delineated discrete HSUs within the aquifer, where limited hydraulic connection exists between individual HSUs. These HSUs have been correlated throughout the LLNL property and appear to be laterally extensive (Noyes *et al., submitted*). An interesting example of hydrodynamics that helped define these HSU geometries is shown by a long-term pumping test conducted at the Treatment Facility D (TFD) site. In this case, wells screened across a discrete zone (HSU 3a/b) did not respond to pumping from wells screened in a zone a few meters deeper (HSU 4) during the 26-day course of the pumping test. Other examples of stratigraphic control on hydrodynamics in the system show similarly striking compartmentalization of the aquifer system (Noyes *et al., submitted*).

A pilot project conducted by the PI at the TFD site, a small (5800 m^2) contaminated area currently undergoing pump and treat remediation, indicates that relatively mature paleosols coincide with previously reported HSU boundaries (Figure 4). Because of the coincidental link between paleosols and the HSUs, we hypothesize that these HSUs represent depositional sequences in the alluvial fan system. Thus, by better defining the alluvial fan stratigraphic character, we should be able to improve site characterization. Additionally, through combined application of transition probability geostatistics within the sequences stratigraphic framework, we believe it possible to capture the multi-scale nature of this complex aquifer heterogeneity for improved groundwater modeling.

Coincidentally, the number and relative apparent maturity of paleosols at the TFD pilot study site appear to correspond to the number and intensity of interglacial periods recorded in deep sea oxygen isotope records. For example, oxygen isotope stages 5 and 11 correspond to longer and/or warmer interglacial periods, and stages 7 and 9 correspond to shorter and slightly cooler interglacial periods (Heusser and Vandegeer, 1994; Rousseau, 1999; Venz *et al.*, 1999; Droxler and Farrell, 2000; Hodell *et al.*, 2000; King and Howard, 2000). A preliminary review of paleosol character at the TFD site shows that paleosol stacking patterns may correlate to this pattern, where better developed soils, shown by thicker illuviated clay coats and redder color, correspond to a position consistent with stages 5 and 11, and less mature paleosols correspond to positions consistent with stages 3, 7, and 9 (Figure 4). Lack of chronologic markers within the strata makes age dating difficult, thus tests of this hypothesis are difficult. However, paleosol character across the study area, determined through sedimentologic description, micromophologic analysis, and geochemical analysis, may help clarify directions for further evaluation of this coincidental relationship. The PI has also submitted samples for pollen analysis to help address this issue, however results of this work are not available at this time.

Backward-in-time Particle Tracking Methods

Transport simulations used to estimate contaminant distribution and transport pathways will employ the random-walk particle tracking method (RWPM) described by LaBolle *et al.* (1998, 2000), LaBolle (2000), and LaBolle and Fogg (2001). This approach applies stochastic differential equations to represent the advection-diffusion equation (ADE). Application of the RWPM to simulate the forward-time ADE predicts future particle distributions, with density representing solute concentration given knowledge of past distributions. When applied to simulate the backward-time ADE, the RWPM equation estimates past particle locations, with density representing probability given that future positions are known (Uffink 1989; Fogg *et al.*, 1999; Neupauer and Wilson 1999; LaBolle *et al.*, 2000).

A strong advantage of using the code produced by LaBolle (2000) is that this procedure accurately models transport in a heterogeneous porous media, where sharp contrasts exist between lithologies (LaBolle *et al.*, 2000). Since the ADE interprets dispersivity and porosity parameters as smooth functions in space, the sharp contrasts between lithologies are often smoothed and poorly honored in standard transport codes. To solve this problem, the RWHet code (LaBolle, 2000) uses an Itô-Euler integration scheme to track changing particle positions with time (LaBolle *et al.*, 2000).

PROPOSED RESEARCH

In this research, we propose to test our overarching hypothesis that detailed analysis of alluvial fan stratigraphy can significantly improve contaminant fate and transport modeling, thereby improving remediation strategy development. To accomplish this, we intend to test the following hypotheses at the LLNL site:

1) Sequences formed within the LLNL alluvial fan complex due to a combination of tectonic and climatic variability, and these sequences contain identifiable and characteristic systems tracts that allow prediction of facies distributions.
2) Sequence boundaries within the LLNL fan system are marked by relatively mature, laterally continuous paleosols formed during periods of extended fan exposure due to stream incision. The base of incised valleys also marks the sequence boundaries.
3) Sequence bounding paleosols form baffles to groundwater movement, thus compartmentalize groundwater flow into the hydrostratigraphic units, and coarse-grained incised valley fill deposits form significant conduits to flow. Erosional breaks in the paleosols form important zones of connection between HSUs.
4) By modeling these facies distributions, we can significantly improve contaminant transport simulations such that they reasonably mimic measured contaminant concentrations.

Additionally, we plan to evaluate paleosol character (e.g., relative degree of weathering) in order to work toward understanding controls on sequence development. For example, we hope to approach answering the question, does the observed paleosol stacking pattern at TFD correspond to length and intensity of interglacial periods, and is this cyclicity observed throughout the study area?

The proposed detailed study area will be a 2.6-km^2 portion of the Arroyo Seco and Las Positas Creek alluvial fan complex located under the LLNL property. The approach to test these hypotheses will consist of three steps:

- Test and generalize the sequence stratigraphic approach for this alluvial fan system by using a combination of core description, well log correlation, and paleosol micromorphologic and geochemical analysis. Aquifer test data also provide evidence on hydraulic interconnectedness within the unit and will be used in developing the stratigraphic model.
- Develop geologically realistic, three-dimensional multi-scale characterizations of the aquifer system heterogeneity using transition probability geostatistics within the sequence stratigraphic framework. To account for uncertainty, multiple realizations will be generated in a Monte-Carlo procedure. Additionally, multiple 'realizations' of the deterministic portion of this modeling approach, produced by students in the PI's classes, will provide additional constraints on uncertainty.
- Simulation of groundwater flow velocity fields and transport in different stochastic realizations to examine the influence of the multi-scale heterogeneity on subsurface hydrology. Direct comparison of these results to previously conducted aquifer tests, tracer tests, and contaminant concentration histories will allow an examination of the accuracy of this integrated approach.

Sequence Stratigraphic Analysis

Goals of the sequence stratigraphic analysis are to 1) test and extend sequence stratigraphic approaches for alluvial fan deposits; 2) investigate paleosol properties for evidence of paleoenvironmental history; 3) determine the spatial distribution and geometry of sequences and systems tracts within the alluvial fan strata; 4) characterize facies within various systems tracts and sequences for use in geostatistical modeling; and 5) investigate methods by which systems tracts can be distinguished in the LLNL alluvial fan system. To accomplish these goals, we intend to:

- Describe sedimentologic and pedogenic features in core;
- Correlate sequence boundaries and systems tracts throughout the study area using core, geophysical log, and hydraulic test data;
- Use micromophologic and geochemical analyses to assess paleosol properties within the alluvial fan succession.

Over 6000 meters of continuous core from 486 borings are available from the upper Livermore Formation, of which we intend to describe all intact portions (Karachewski, *pers. comm.*). Sedimentologic characteristics, such as grain size distribution, sedimentary structures, pedogenic structures and features, biogenic features, and color, will be included in these core descriptions. Correlation to geophysical log properties will allow estimation of sediment properties in locations where only geophysical log data are available (from an additional 300 wells). A positive test of the applicability of sequence stratigraphic concepts to this alluvial fan system will be a determination of whether or not mature paleosols can be correlated across the alluvial fan complex (hypothesis 2), and whether systems tracts consisting of sediment with distinctive sedimentary character in predictable locations exist within each sequence (hypothesis 1).

Because soils of varying maturity developed throughout the complex depositional history of the alluvial fan, detailed micromorphologic and geochemical analyses of paleosols will be used to determine small- and intermediate-scale depositional patterns and variable pedogenic alteration at the site, thus aiding interpretation of paleoenvironment variability within or across sequences. Thin sections will be made at 20-cm spacing over selected intervals in several cores for micromorphologic analysis, and supporting geochemical analysis of corresponding samples will be conducted. We plan to assess molar ratios of relatively inert geochemical indicators (e.g., Ti/Y, Ti/Zr, Zr/Y, and Al/Ti) to detect lithologic discontinuities (McCarthy *et al.*, 1997a). Additionally, we will analyze ratios of mobile to essentially immobile elements (Fe/Ti, Al/Fe, Ca+Na/Ti) and the CIA (Nesbitt and Young, 1982) to assess the degree of weathering in paleosols (Feitjel *et al.*, 1988; Maynard, 1992; McCarthy *et al.*, 1997a). Proper extraction methods are important for guaranteeing useful geochemical results (Ross and Wang, 1993), thus appropriate extraction methods for individual elemental analysis, as listed in USDA-NRCS (1996), will be used to prepare samples for Atomic Absorption Spectrometry (AAS), X-ray Fluorescence (XRF), and/or the Inductively Coupled Plasma – Mass Spectrometer (ICP-MS). These analytical systems are available at the MSU Department of Geological Sciences.

Since detailed micromorphologic and geochemical assessment can not be conducted over the entire area, stratigraphic intervals for this detailed analysis will be selected to represent key depositional zones identified in the overall stratigraphic assessment. For example, at the TFD pilot study site, the sedimentary character of Units B and E appear to contrast in style, where a greater proportion of coarse-grained sediment dominates Unit B (Figure 4). Paleosol micromorphologic analysis, combined with stratigraphic correlation and geochemical testing, would be conducted across these zones (using core from the well with best recovery and preservation of sedimentologic features) in order to examine possible paleoenvironmental controls on these differences. Geochemical analysis will only be completed in pedogenically modified sections of the selected intervals to reduce costs. We plan to examine similar, correlative zones in other portions of the aquifer system based on regional correlations across the site. Based on stratigraphic thickness observed at TFD, and understanding that these units thicken to the northeast (in distal, more basinal portions of the fan complex), we expect to evaluate 80 meters of core in this detailed manner. Cores for this analysis will also be selected to achieve understanding of proximal-distal relationships on the alluvial fan.

3D Geological Characterization and Modeling

After the stratigraphic framework is developed for the area, Markov chain models of spatial variability will be developed for each sequence and systems tract within the stratigraphic succession.

Vertical transition probabilities for the models will be directly measured from core and geophysical well log data. Weissmann *et al.* (1999) showed that mean lengths and other coefficients required for Markov chain models can be determined using textural information from soil surveys. Additionally, excellent aerial photographs and areas of close-spaced drilling at the LLNL site offer information on lateral facies relationships for constructing these lateral models.

Several detailed simulation areas will be selected within the overall study area in order to model specific aquifer test results and to test remediation effectiveness. These detailed simulation areas will be large enough to contain influence of pumping within the simulation boundaries. In accordance with observed spatial continuity of intermediate-scale facies observed at the TFD pilot study site, block size in the simulations will be approximately 1m x 1m x 0.3m and will consist of up to 1.5 million nodes. The PI and colleagues have conducted simulations and groundwater modeling with grids of similar size over the last several years. A Monte Carlo procedure, in which multiple realizations are produced from the Markov chain model, will be used to account for uncertainty in local patterns of heterogeneity. Additionally, since the stratigraphic framework relies on deterministic modeling (e.g., stratigraphic correlation between wells), and different geologists will produce different results when asked to produce such a deterministic model, multiple 'realizations' of large-scale features will be produced through long-term classroom projects (as will be discussed further in the 'Educational Development' section of this proposal).

Groundwater Flow and Contaminant Transport Modeling

We are interested in developing the detailed geologic simulations to both distill understanding of how complex stratigraphy affects groundwater flow and contaminant transport and to evaluate the effectiveness of this approach to predicting and characterizing aquifer test results and remediation strategies. Many questions about flow and transport arise that may be answered by this analysis, effectively testing our third hypothesis:

- Do laterally extensive paleosols compartmentalize the flow system, dividing the aquifer system into HSUs, and do breaks in these paleosols form important connections between HSUs?
- Can this modeling approach effectively match character of aquifer tests and plume geometries?

As in the Kings River Alluvial Fan study, we will use MODFLOW to simulate groundwater flow and a random walk particle tracking method, RWHet (LaBolle, 2000), to solve the advection-dispersion equation. This groundwater flow and contaminant transport modeling will be conducted in collaboration with LLNL hydrogeologists. Observed aquifer test results, contaminant concentration measurements, and tracer test data will be directly compared to simulated results for a verification of this modeling approach. A positive test of our third hypothesis would result in modeling results that reasonably match drawdown response from aquifer pumping tests and tracer test results.

Boundary conditions representing pumping, recharge, and lateral boundary fluxes will be developed to approximate observed groundwater velocities at the study site. Where possible, the mesh will extend to natural hydrologic boundaries. In other areas, the lateral boundary fluxes will be estimated through linkage to larger-scale regional models at the site that have been produced by LLNL hydrogeologists. Since the property is currently a laboratory campus, winter rainfall, summer lawn irrigation, and intermittent flows in the creeks are sources of recharge. LLNL scientists have estimated recharge rates based on these factors (Blake, *pers. comm.*).

Hydraulic conductivity (K) estimates for lithologic categories determined in the geological modeling are available from core analysis and aquifer test results at the site. Additionally, data on average storage coefficients and porosity for each facies are available.

Contaminant transport will be simulated using both forward and backward-in-time particle tracking approaches (Fogg *et al.*, 1999; LaBolle *et al.*, 2000). Results of the backward solution will be in the form of maps showing origin and approximate timing of contamination at the water table. These results can be checked against known contaminant sources and timing within the study site. Forward-in-time modeling will be used to assess accuracy of these models relative to tracer tests conducted at the site.

EDUCATIONAL DEVELOPMENT

An exciting aspect of this research is that it affords many excellent opportunities for students in both the research and classroom settings. The obvious area where students will gain from this proposed project is in the research setting, where a handful of students participate in all aspects of the project. Additionally, however, many aspects of this project can also be 1) conducted in the classroom as long-term applied projects and 2) distilled into level-appropriate exercises to enhance student understanding of heterogeneity.

These latter aspects of educational activity are of critical importance to this proposed work. Though the importance of incorporating geologic concepts and models into hydrogeologic characterization is widely recognized as critical for aquifer characterization at contaminated sites, inclusion of geologically-based heterogeneity assessment is typically lacking in many hydrogeology courses. A review of commonly used introductory hydrogeology textbooks (e.g., Freeze and Cherry, 1979; Fetter, 2001) indicates that evaluation of groundwater systems in typically heterogeneous aquifers is absent. In most cases, the geologic complexity is mentioned but the actual influence of small and intermediate-scale heterogeneity is minimally presented. Similarly, syllabi of undergraduate-level hydrogeology courses across the country, as determined by a website review, indicates that few classes expose students to the importance of detailed characterization for contaminant transport in any detail.

A possible reason for this ‘gap’ in our students’ training could be that examples of applications of geologic/hydrologic assessment are not generally available at an appropriate level for most students to comprehend. Through publication of this research as accessible exercises for undergraduate students, both in appropriate journals (e.g., Journal of Geoscience Education, Journal of College Science Teaching) and the Internet, the concepts at the heart of this research (methods for understanding heterogeneity through combined geologic/hydrologic modeling) will reach a broader audience.

An important aspect of educational materials developed under this proposal is active involvement of students in the learning. Through a combination of lecture and various activities, students participate more fully in the learning process. This active style has been shown to enhance student comprehension and motivation, and it tends to involve students with diverse learning styles and backgrounds (Bykerk-Kauffman, 1995; Macdonald and Bykerk-Kauffman, 1995; Johnson *et al.*, 1991, 1998).

The following sections outline examples of how students will directly gain from aspects of this proposal in both the research and classroom settings.

Research setting:

In terms of research opportunities, at least four graduate students will be involved in analysis of details outlined in this proposal – one at doctoral level and the other three at Master’s level. The doctoral student for this study, Leslie Mikesell, has already been identified and has shown interest in evaluating the detailed stratigraphy and paleosol morphology at the site. Her current Master’s program is focusing on mineral weathering and chemical transformations in modern Michigan soils. She has proposed to apply similar techniques to paleosol interpretation at the LLNL site and has already begun review and evaluation of the project area. Her ultimate goal is to teach at a small, liberal arts college. This project will help broaden her background by combining aspects of basin analysis, stratigraphy, hydrogeology, soil science, geomorphology, mineralogy, and geochemistry to accomplish the research goals, thus preparing her to effectively teach a broad range of topics in a department with few faculty members.

The Master’s level students for this project will be recruited to conduct detailed hydrogeologic assessment within the stratigraphic framework developed by Leslie and myself. These students will also participate in the overall characterization of the study site through core analysis and correlation. I hope to recruit the first student in the upcoming year to expand and evaluate the TFD study site. Most of our Master's-level students intend to work in either the petroleum or environmental industries, and the combination of basic and applied research will prepare them to effectively operate in these fields.

In addition to the graduate researchers, several opportunities exist to involve undergraduate researchers in the project. Undergraduate research has been shown to be a critical part of one's educational process, not only preparing the student for future graduate level research or the workplace, but also reinforcing concepts learned in the classroom (Mogk, 1993; NSF, 1996; Boyer Commission, 1998; Abraham and Hoagland, 1998; Shellito *et al.*, 2001). At present, three undergraduate researchers are involved in various projects in my laboratory, including the LLNL pilot study. These students are given responsibilities of data base management, data drafting, core description, and stratigraphic modeling. The sub-project complexity for the undergraduate researcher is gauged depending on the student's proven abilities, with increasing responsibilities offered as students show interest and ability. This involvement in research also affords these students the opportunity to present research at regional and national meetings (e.g., Bennett and Weissmann, 2001).

Another important benefit for all students involved in this research is the exposure and opportunity to work with LLNL scientists on the project. Through contact with these individuals, the students will have opportunities to draw information from several experts in hydrogeology to answer both research and career related questions. Additionally, LLNL staff run weekly seminars on issues related to hydrogeology and geology, and these students can partake in these meetings. Finally, these students will also benefit from co-advising by Dr. David Hyndman, another MSU faculty member who has significant experience evaluating and modeling complex groundwater systems.

Classroom setting:

Not only will several students be exposed to this research by conducting aspects of the work, but also the data set provided by this research can be incorporated into long-term projects, in-class exercises, and homework assignments. Additionally, as previously stated, I plan incorporate aspects of this research directly into the classroom. This research will primarily be incorporated into two classes – Reservoirs and Aquifers, an upper division undergraduate-level class that focuses on geologic characterization of groundwater and petroleum systems, and Basin Analysis, a graduate-level course that focuses on advanced concepts related to basin-scale stratigraphic evolution. Examples of long-term projects and exercises show potential products of this work.

Long-term class project

A planned long-term project for the Reservoirs and Aquifers class, scheduled to be taught during Spring semester, 2002, shows how students will conduct aspects of the research. I plan to use core descriptions, geophysical well log data, and hydraulic test data from the TFD pilot study site for this work. The project will be conducted in three stages, where students learn key concepts required to perform tasks through lecture and activities. Learning objectives are threefold: 1) students will know how to evaluate facies from geophysical well logs, correlating them to core descriptions; 2) students will be able to correlate facies within complex alluvial systems; and 3) students will be able to use geostatistics for modeling facies distributions in an aquifer or reservoir. The complexity of this project requires that it be run throughout the semester.

In the first stage of the project, students describe a portion of LLNL core, compare these core descriptions to geophysical log data, and develop a facies 'calibration' for the geophysical logs. During this portion of the process, students will be concurrently learning geophysical well log interpretation methods. The second stage of this project involves stratigraphic correlation at this site. Correlation methods learned through this project are applicable to many subsurface characterizations, so this project work will be enhanced through experiencing larger-scale correlation exercises (e.g., a Michigan Basin well log correlation exercise). Through this work, students will construct the stratigraphic framework at the TFD site. Importantly, results from this stage will provide the research side of this proposal with multiple 'realizations' of the deterministic stratigraphic framework, thus aiding evaluation of uncertainty in our models and involving classroom students directly in the research.

The final stage of this project involves development of Markov chain models for each sequence and application of these models in transition probability geostatistical simulation. Students will learn the theory and application of both standard and transition probability geostatistical techniques during this part of the project and work in teams to produce realizations of the TFD study site. This stage of the project is conducive to a 'jigsaw' style activity (Tewksbury, 1995, unpublished; Aronson and Patnoe, 1997), where a small group of students are assigned to each sequence. Once these groups successfully simulate their sequence, one member from each group will form a new group that has the responsibility of combining these results into the final realization. These final groups will also compile a brief report. Though time constraints keep us from being able to apply groundwater simulation in these realizations during the semester, students who later take Advanced Hydrogeology from Dr. Hyndman will be able to use these results for a groundwater modeling project in his class. Additionally, the graduate student responsible for analysis at that site will conduct groundwater flow and contaminant transport modeling through these realizations. In future years, detailed analysis of other sites will be conducted in a similar manner (though with revisions as experience demands).

In- class and/or homework exercises

Several short-term classroom activities can be formed from data and results of this research. Dissemination of these activities through publication, presentation at meetings, and Internet data release will provide exercises that can be used in most undergraduate classrooms to aid in combining geologic concepts with hydrogeologic models.

An exercise that is being developed for Reservoirs and Aquifers shows how the results from this work can be directly translated into homework or laboratory exercises. In this homework exercise, students evaluate the TFD pumping test results, previously mentioned. This exercise offers the opportunity for students to 1) evaluate pumping test data, thus reviewing methods learned in a previous hydrology class and 2) evaluate the strong influence heterogeneity has on cone of depression evolution. Learning objectives of this assignment focus on student understanding of pumping test results and analysis of these data in heterogeneous systems.

The first stage of this exercise uses the standard Theis (Theis, 1935) and Jacob (Cooper and Jacob, 1946; Jacob, 1950) methods to evaluate drawdown at wells within the TFD site. From this assessment, the students will predict drawdown at several wells of varying distances. A comparison to actual drawdown at observation wells will show the strong influence of heterogeneity at the site. By mapping actual drawdown with time, then comparing these results to sand isopach maps of the sites, the students will work through a clear example of the influence of heterogeneity. In this case, the hydraulics of the pumping test are controlled by a single channel sandbody that is oriented northwest-southeast through the TFD site. This becomes very clear when mapping or plotting the drawdown through time at these wells. This exercise should lead to a discussion of clearly evaluating assumptions when applying any model (in this case, the Theis or Jacob models). To aid student's grasp of this concept, movies produced using our modeling results from the research will show modeled drawdown with pumping at this site. This exercise, once completed and tested, will be published (possibly in Journal of Geoscience Education) and available on the Internet.

EXPECTED RESULTS AND BENEFITS

This research will result in 1) a significant step toward understanding stream-dominated alluvial fan hydrostratigraphy; 2) a test and refinement of the sequence stratigraphic approach to defining stream-dominated alluvial fan facies distributions; 3) a demonstration of the significant role that heterogeneity plays in contaminant plume geometry and evolution, along with a method to approach evaluating and planning remediation strategies; and 4) development of accessible examples of the role of heterogeneity on groundwater flow and contaminant transport for use in classroom settings. Additionally, this research will aid in development of effective remediation efforts for the LLNL site.

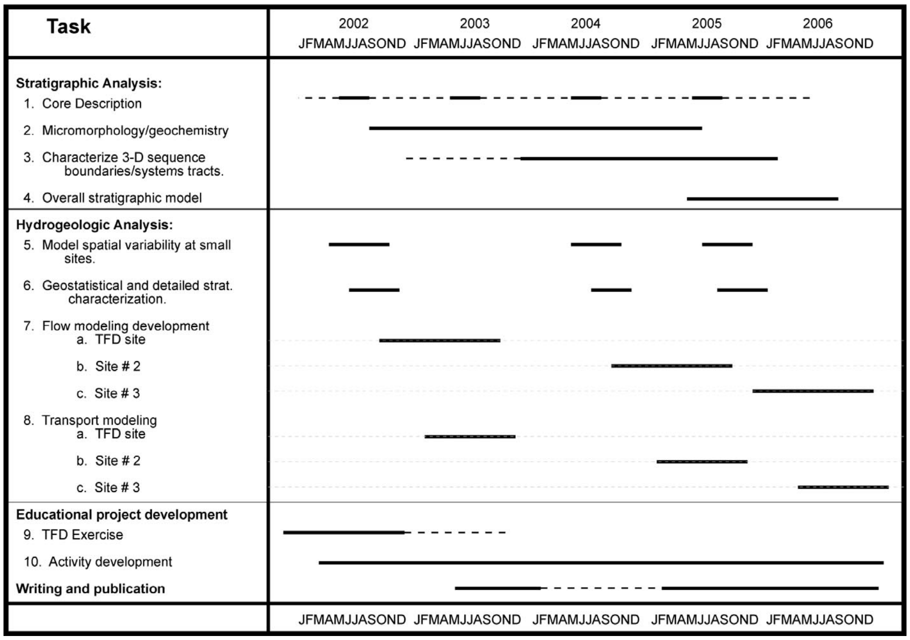
The proposed work focuses on key issues identified by Shanley and McCabe (1994; 1998) by evaluating continental rocks in a sequence stratigraphic framework, thus determining (1) whether a continental equivalent to a parasequence exists, and (2) whether systems tracts can be described in continental settings. Additionally, the educational component involves undergraduate students in active research (NSF, 1996), and helps produce activities for hydrogeology classrooms.

PRIOR RESEARCH AND EDUCATIONAL ACCOMPLISHMENTS

The combination of industry and government experience along with academic accomplishments provides me with a unique background to conduct this research and education program. During my tenure in the petroleum industry, I gained experience in subsurface geological assessment, including application of sequence stratigraphic approaches, and geophysical well log analysis techniques. This experience proved invaluable during development and application of sequence stratigraphic concepts on the Kings River Alluvial Fan system. By combining this new approach to assessing alluvial fan systems with hydrogeologic characterization (Weissmann and Fogg, 1999; Weissmann *et al.*, *in press*), we have been able to advance hydrogeologic modeling methods in these complexly heterogeneous systems. The novelty of this approach led to an invitation as one of nine keynote speakers for the SEPM Aquifer Sedimentology Symposium held in September, 2000.

Additionally, I strive to constantly improve teaching through innovative approaches. While working on my PhD at UC Davis, I was a ‘Professors for the Future’ fellow and a participant in the Program for College Teaching, a selective program that involved mentored teaching and numerous activities to aid future faculty in developing their teaching skills. One result of the Program in College Teaching was publication of an article outlining approaches to mentoring undergraduate researchers (Shellito *et al.*, 2001). Finally, I was selected to attend the NSF and NAGT sponsored Workshop for Early Career Faculty in the Geosciences during summer, 2000, and have incorporated many ideas from this workshop into courses taught over the past year.

PROPOSED SCHEDULE



FIGURES

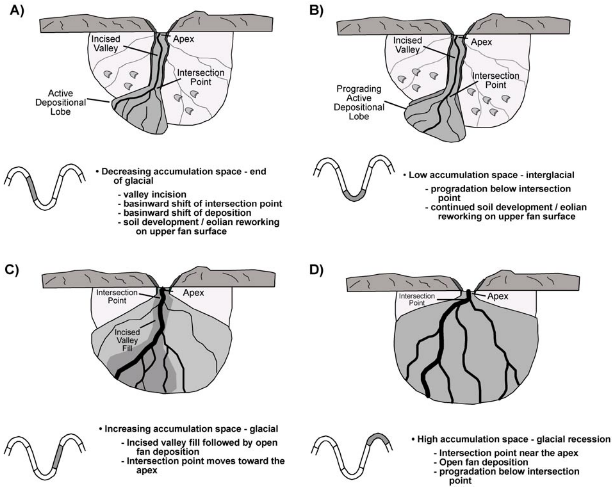


Figure 1: Sequence stratigraphic cycles on an alluvial fan. Darker shading indicates active portions of the alluvial fan. A) Accumulation space decrease. B) Low accumulation space. C) Accumulation space increase. D) High accumulation space. (From Weissmann *et al., in press*).

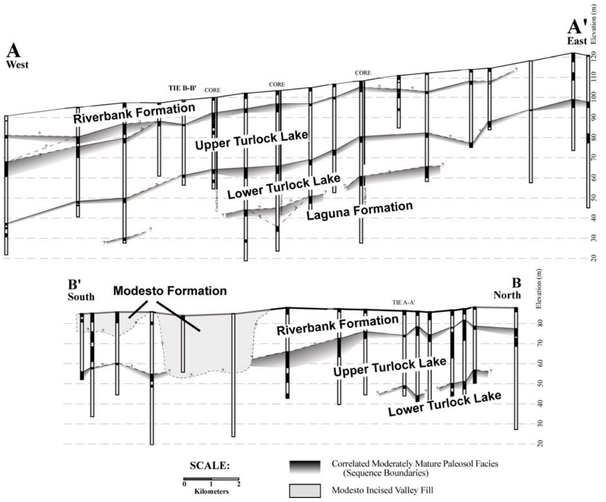


Figure 2: Cross sections through the upper Kings River Alluvial Fan. Section A-A' is parallel to depositional dip, and section B-B' is parallel to depositional strike. (From Weissmann *et al.*, *in press*).

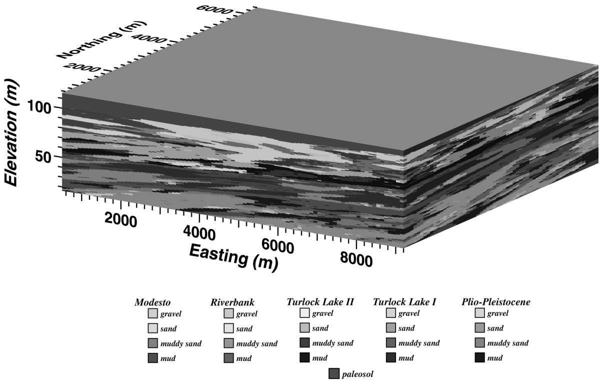


Figure 3: A geostatistical realization from the Kings River Alluvial Fan derived from incorporation of sequence stratigraphy and geostatistics (from Weissmann and Fogg, 1999).

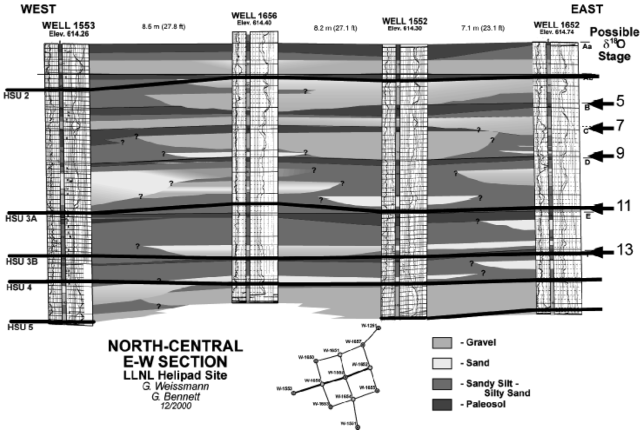


Figure 4: Detailed stratigraphic cross section through the LLNL TFD study site. Note that mature paleosols (dark gray) align with previously defined HSU boundaries. Additionally, apparent paleosol maturity appears to align with interglacial length and intensity indicated by the marine oxygen isotope record.

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