CHILE SLOPE SYSTEMS

University of Calgary
Virginia Tech
Colorado State University

JOINT INDUSTRY PROJECT

Chile Slope Systems (CSS) Phase II (2016-2019): Architectural Analysis and Modeling of Outcropping Slope Deposits, Magallanes Basin, Chile

Project Motivation: The deposits of deep-water systems, despite recent advances, are the most poorly constrained in the clastic sedimentary record. An integrative approach is required to tackle the unique exploration, field development, and reservoir management challenges posed by slope reservoirs. The application of outcrop analogs is a proven method for reducing uncertainty in subsurface prediction/characterization and reservoir model construction.

Objectives: The JIP is focused on deciphering the processes of sediment transfer (i.e., erosion, bypass and deposition) across slopes, motivated to better constrain hydrocarbon distribution and to optimize recovery:

Objective 1: Basin/Exploration-Scale
Constrain the regional chronostratigraphic framework and exploration-scale context for reservoir-scale models developed from the deep-marine Tres Pasos Fm and genetically linked shallow-marine Dorotea Fm (Fig. 1A).

Objective 2: Conceptual Models/Depositional System- to Reservoir- Scale
Document the bed-scale sedimentology and stacking patterns of slope channel and intraslope fan deposits with an emphasis on development of conceptual models that can be used to improve prediction laterally away from 1-D data (e.g., well logs, cores) (Fig. 1B, C).

Objective 3: Architectural models/Reservoir-Scale
Characterize the stratigraphic architecture of slope deposits through construction of a library of outcrop-constrained three-dimensional architectural models in Petrel. Analysis includes compilation of quantitative data and metrics that describe stacking patterns and internal (e.g., intra-channel) heterogeneity (Fig. 2A, B).

Objective 4: Geomodeling/Reservoir-Scale
Leverage knowledge, data, and derived statistics from architectural model analysis to generate reservoir geomodeling strategies. Modeling studies test the impact of reservoir architecture and rock properties on fluid flow and seismic reflectivity responses (Fig. 2C, D).

People: The JIP consists of an integrative collaboration of professors, postdoctoral researchers and students with geology and engineering backgrounds from the University of Calgary, Virginia Tech, and Colorado State University. The principal investigators are:

Steve Hubbard
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Experience:
- Professor, 2006-present
- Ph.D., Stanford (2006)
- CSS JIP P.I. (2007-2016)
- Prof. geologist : 3 yrs

Brian Romans
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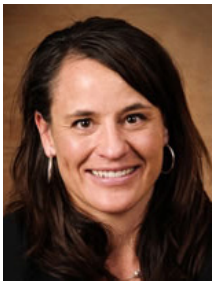
Experience:
- Professor, 2011-present
- Ph.D., Stanford (2008)
- CSS JIP P.I. (2012-2016)
- Prof. Geologist: 6 yrs



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Experience:
- Professor, 2011-present
- Ph.D., Stanford (2011)
- CSS JIP P.I. (2012-2016)
- Prof. Geomodeler/Engineer: 7 yrs

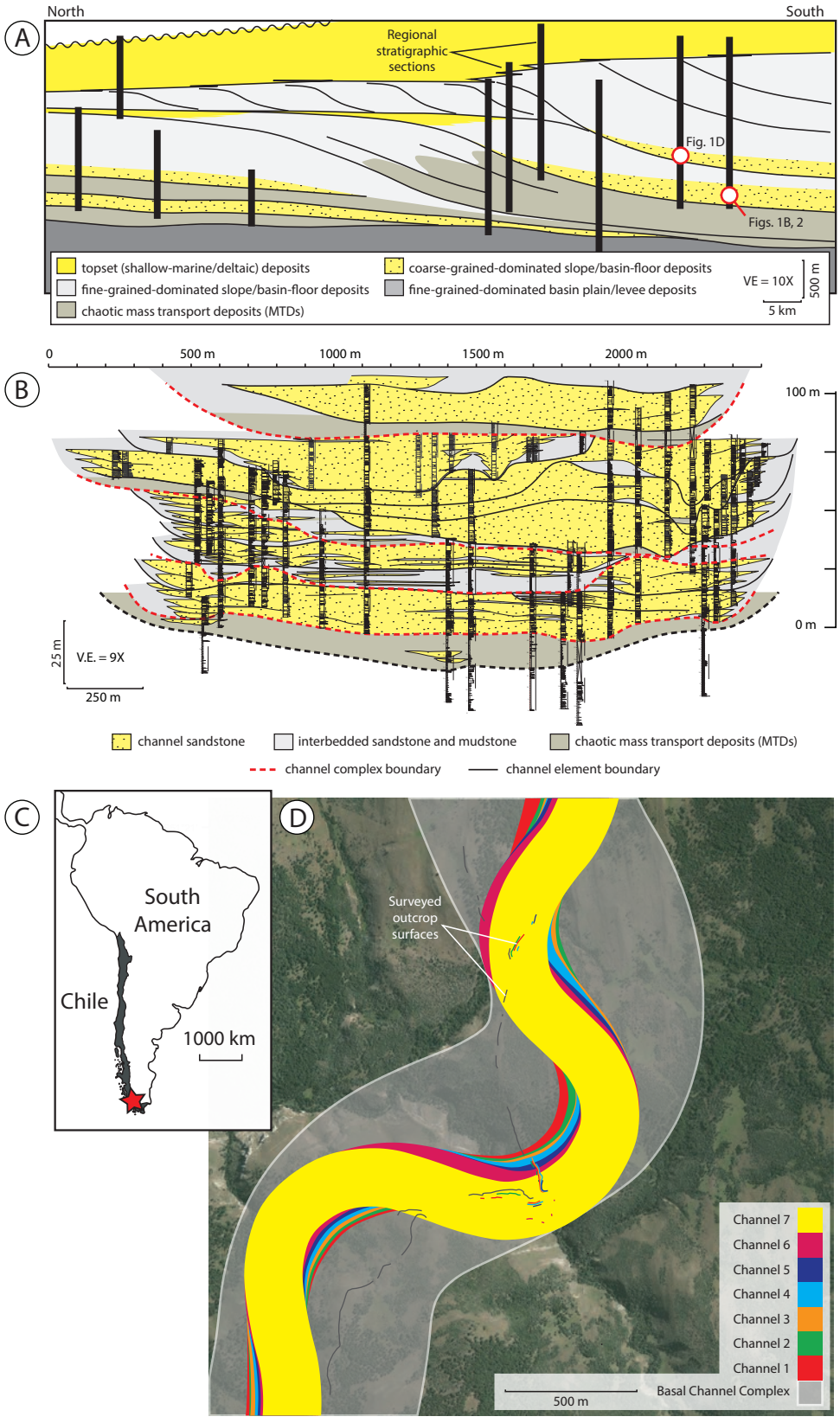

Figure 1. (A) Regional depositional dip-oriented stratigraphic cross-section of Upper Cretaceous Tres Pasos and Dorotea formations, Magallanes Basin, southern Chile. Composite stratigraphic sections are indicated, which constrain a northern slope system dominated by ponded sandstone closely associated with widespread mass-transport deposits; and a southern slope system dominated by a high relief (>1000 m) slope clinoform system. Detailed projects are assessed in the context of their depositional position on this paleo-margin. Locations of images in proposal indicated by red circles. (B) Conceptual stratigraphic cross-section of stacked slope channel bodies from the Laguna Figueroa locality, revealing a composite sedimentary package comparable in dimensions and internal character to numerous slope channel system reservoirs. (C) Inset map of South America with the location of the Magallanes Basin denoted by star in southern Chile. (D) The sinuous channel system mapped is grounded in outcrop observations in the southern portion of the transect in Part A; this outcrop reveals analogous architecture to a variety of slope reservoirs.

PROJECT HISTORY: The stratigraphy of deep-water outcrops in the Magallanes Basin has been studied for >50 years by researchers from both academia and industry. The 3 principal investigators gained expertise in the region as Ph.D. students with the Stanford Project on Deep-water Depositional Systems. Starting in 2007, Steve Hubbard led an industrial consortium focused on slope channel deposits of the Tres Pasos Formation. The consortium had 3 members in 2010, and 7 members in 2012. The growth in interest in the consortium, and exceptional opportunity for continued research in the area, inspired expansion of the project into a multi-university JIP, and in 2012, Phase I of CSS was underway with 13 industry sponsors. This proposal outlines the rationale and plans for a second three-year phase to begin in 2016.

PROJECT BACKGROUND: The Upper Cretaceous Magallanes Basin of southern Chile contains >3 km of deep-marine strata, including several coarse-grained units that record turbidite depositional system evolution. The unique tectonic history of this basin has resulted in a regionally continuous outcrop belt of high-relief slope systems, the deposits of which comprise the Dorotea (topset) and Tres Pasos (slope) formations (Fig. 1). The basin filled axially, with older (northern) slope deposits that include sandstone architectures influenced by topography from mass transport deposits and syndepositional faulting. Southward, clinoforms that represent a series of paleoslope profiles that formed as the bathyal Magallanes Basin filled, are on the order of >1 km high (paleobathymetric relief) and at least 30-40 km long (from paleo shelf edge to lower slope). Stacked channel complexes up to 300 m thick from this region have been used as analogs to reservoirs around the globe. Seismic-scale constraint on basin-filling patterns provides exceptional stratigraphic context within which to investigate detailed, reservoir-scale architecture.

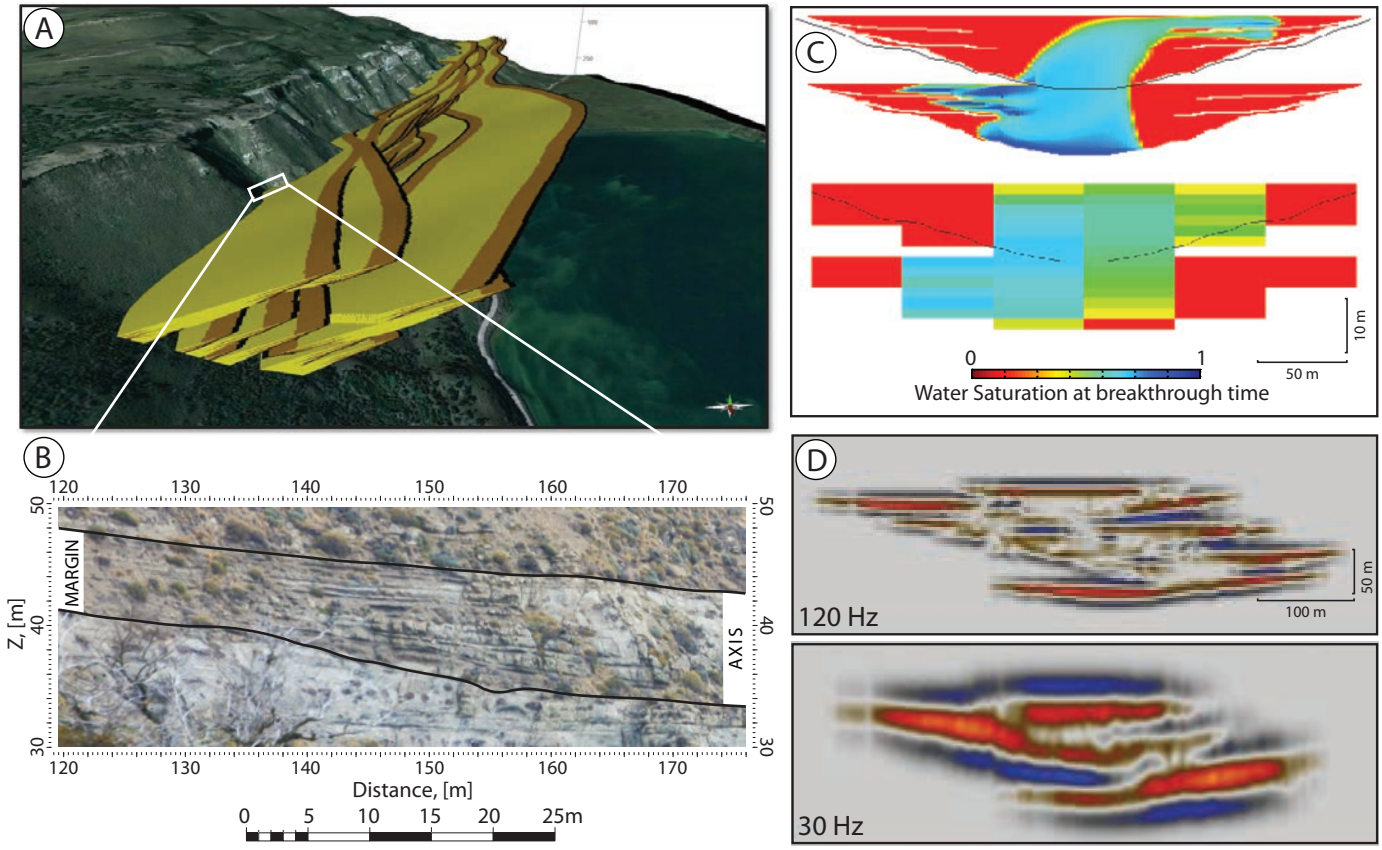

Figure 2. (A) South-facing perspective image of channelized strata of lower section exposed at Laguna Figueroa (Tres Pasos Fm) highlighting modeled channel elements, which are ~250 m wide and 14 m thick. Yellow internal channel architecture represents sandstone-rich channel axis facies and orange and brown colors represent sandstone-poor margin facies. (B) Photograph of the axis-to-margin transition constraining intra-channel architecture. The link between bed scale heterogeneity to channel architecture and then to channel stacking is all captured by detailed measured sections and surveyed stratigraphic surfaces (<10 cm resolution differential GPS). (C) Flow simulation study results showing the dominant role that the axial channel facies play in controlling fluid movement (top), with optimized coarse grid and effective property modeling capturing the same fluid flow behavior (bottom). (D) Synthetic seismic profiles (extracted from 3-D seismic model) used to assess interpretability of internal channel architecture and channel stacking patterns; these efforts are aimed at optimization of seismic data usage in geomodeling workflows.

PHASE I RESULTS AND DELIVERABLES: Phase I work has generated a wealth of fundamental outcrop data (e.g., measured sections), high-resolution GPS surveys from several outcrops, construction of four 3-D architectural models (in Petrel), and two synthetic seismic models (Table 1). A general workflow and examples of results are presented in Figure 2. These analyses have led to numerous scientific and applied outcomes including a refined conceptual model to explain slope channel-fill patterns, documentation and interpretation of reservoir-scale slope channel stacking patterns, static connectivity insights for channelized reservoir strata, and reservoir flow simulation experiments of intra- and inter-channel dynamic connectivity. Phase I has supported the research of 6 M.S. students, 4 Ph.D. candidates, 1 post-doc, and the 3 principal investigators. Research results have been delivered in a timely manner through annual consortium meetings and field workshops, site visits, and online (http://www.chileslopesystems.com).

Slope Architecture Type	Strat Unit (Outcrop locale)	Research Objectives/Deliverables: Conceptual Models / Depositional System- to Reservoir-Scale → Architectural Models / Reservoir-Scale → Geomodeling / Reservoir-Scale				
		Sed/Strat Characterization	Hi-Resolution Surveying	3-D Architectural Model in Petrel	Reservoir Modeling / Flow Simulation	Synthetic Seismic Model
Vertically stacked channels	Figueroa Lower (Laguna Figueroa)	✓	✓	✓	✓	✓
Vertically stacked channels	Figueroa Upper (Laguna Figueroa)	✓	✓	✓	✓	✓
Vertically stacked channels	Figueroa Lower (Hotel)	✓	✓	✓		
Laterally stacked channels	Figueroa Lower-Upper (Alvarez Ridge)	✓	✓	✓	✓	✓
Sinuous, asymmetric channel complex	Puma (Puma-Picana Confluence [PPC])	✓	✓	✓	✓	✓
Laterally migrating channel complex	Northern TP (Glory at Cerro Cagual)	✓	✓			✓
Channel-lobe transition zone (CLTZ)	Figueroa Lower (Arroyo Picana)	✓	✓	✓	✓	✓
MTD-influenced intra-slope fans	Northern TP (Rio Zamora)	✓	✓	✓		✓
Growth-fault-ponded slope fan	Chingue (El Chingue Bluff and Cerro Sol)	✓	✓	✓		✓

✓ Phase I Results ✓ Proposed (Phase II)

Table 1. Geomodel library status, including models developed to completion in Phase 1, and models planned for Phase 2.

PHASE II RESEARCH PLAN: We will continue to address the four project objectives through a series of focused activities, outlined in Table 2. In all instances, the studies will be accomplished through the collective effort of students and principal investigators. Geomodels are an important deliverable from this JIP, grounded in outcrop characteristics; Table 1 outlines the state of the JIP geomodel library including completed models and those in various stages of completion that will be completed in Phase II.

DELIVERABLES AND SPONSOR BENEFITS:

- Access to 3-D architectural models (Petrel projects), data, posters, presentations, and reports/papers via a password-protected website (http://www.chileslopesystems.com).
- Annual opportunities for interaction with PIs and graduate students:
  - Up to two people per company are invited to attend an excursion to visit the field area.
  - A one-day meeting associated with the timing/location of the annual AAPG Meeting to deliver findings from previous year and discuss ongoing and future research activities.
- Companies will receive annual progress update of findings highlighting the results of the JIP.
- Opportunities to interact with PIs and students at company-specific site meetings.
- Companies will be acknowledged on all disseminated material.

Table 2. Proposed CSS Phase 2 project list.

Projects	Timeline: 2016	2017	2018	2019
Basin/Exploration-Scale (CSS Objective 1)				
Strontium isotope stratigraphy of the Tres Pasos Formation: Improving basin chronology and insights into intra-basinal sediment recycling	■	■		
Detrital zircon geochronology of the Tres Pasos Formation: Testing regional clinoform correlations and estimating basin-scale progradation rates	■	■		
Conceptual Models/Exploration- to Reservoir-Scale (CSS Objective 2)				
Characterization of upper-slope facies and architecture along the Figueroa clinoform: Insights into up-dip stratigraphic traps	■	■	■	■
Exploring sedimentary body architecture downdip of channel complexes, southern Figueroa Clinoform	■	■	■	■
Facies and bed-scale characterization of a growth-fault-influenced intra-slope fan, Chingue member, Cerro Solitario	■	■		
Architectural Models/Reservoir-Scale (CSS Objective 3)				
From conceptual models to reservoir modeling inputs: Characterizing the variable stratigraphic expression of slope channel fills	■	■	■	
Architecture and spatial distribution of MTD-influenced intra-slope fans, Rio Zamora	■	■	■	■
Geomodeling/Reservoir-Scale (CSS Objective 4)				
Quantifying inter- and intra-channel architectural controls on reservoir performance	■	■		
Reservoir modeling and flow simulation of asymmetric channel fills of a high-sinuosity channel complex, Puma Clinoform	■	■	■	■
Quantifying the information content of seismic attributes for reliable stratigraphic interpretation and reservoir model prediction	■	■	■	■

ADDITIONAL INFORMATION:

For an electronic copy of this document and supplemental information, please visit:
http://www.chileslopesystems.com/objectives_proposals

Joint Industry Project

Consortium Terms

Architectural Analysis and Modeling of Outcropping Slope Deposits

Magallanes Basin, Chile

General Terms

- *Project Leader:* Steve Hubbard, University of Calgary
    - *Project Co-Leaders:* Brian Romans, Virginia Tech & Lisa Stright, Colorado State University
- *Term of Agreement:* 3 years (2016-2019), option to opt out of the agreement at the conclusion of each project year
- *Financial Contribution:* $43,750 USD/year/per sponsor, which includes 25% for indirect costs
    - Consortium funds will be paid to and held at the University of Calgary
    - Calgary will distribute project funds accordingly to the Project Co-leaders
- *Research Results:* IP rights from Project Co-Leaders will be consolidated at Calgary
    - Sponsors will be given a license to research results for internal use

Benefits to Consortium Membership

- *Research Results:* non-exclusive, world–wide, perpetual, non-exclusive right to use all Research Results internally
    - Access to data, posters, presentations, reports & papers through a password protected website
    - Annual scientific and financial progress report of findings as well as a final summary report
- *Field Opportunities:* at least two individuals per Sponsor will be invited to attend an excursion to the field areas with the Principal Investigators and students
- *Annual Consortium Meeting:* A meeting associated with the timing & location of the annual AAPG meeting to discuss research results and plans
- *Recognition:* Sponsors will be acknowledged on all disseminated material