CHILE SLOPE SYSTEMS

University of Calgary
Virginia Tech
Colorado State University

JOINT INDUSTRY PROJECT

Chile Slope Systems Phase 4 (2022-2025):
MODELS AND PREDICTIONS OF SLOPE SYSTEM RESERVOIRS

http://www.chileslopesystems.com

Project Mission: We develop predictive stratigraphic models of slope systems from world-class outcrops, using qualitative and quantitative analysis of sedimentary processes and products to improve reservoir predictions and test impacts on reservoir performance.

Summary of Proposed Research: CSS Phase 4 will build on Phases 1-3 (2012-2022) with a continued focus on exceptional outcrop belts and their relevance to subsurface characterization and prediction. We plan to expand into other stratigraphic units in the Magallanes Basin (Chile) and the Nanaimo Basin (Canada), as well as explore other world-class outcrop belts and subsurface datasets. A new emphasis in CSS Phase 4 is to utilize our robust digital database from Phases 1-3 with a cross-cutting ***Integrated Data Analytics Approach***. Key research questions, our unique approach to finding answers, and anticipated impacts of our proposed Phase 4 research are outlined in Table 1. Access to our new website and database is available to any former or current sponsor with provided login information. Prospective sponsors can access a limited preview of the web content.

Why CSS?: For over a decade, our interdisciplinary approaches have been leveraged by our sponsors to address reservoir characterization, prediction, and modeling questions. We provide relevant educational opportunities through safe and effective field excursions, workshops, and seminars that take advantage of our extensive catalog of outcrop and modeling studies that connect field to subsurface. Our comprehensive database of outcrop measurements capture tens of thousands of robust and consistently collected data points that are, collectively, the foundation for ongoing and proposed analytics efforts. These data are hosted on an interactive, web-driven platform that is contextually linked to supporting literature (e.g., presentations, papers, and field guides), allowing user-specific querying and knowledge transfer.

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

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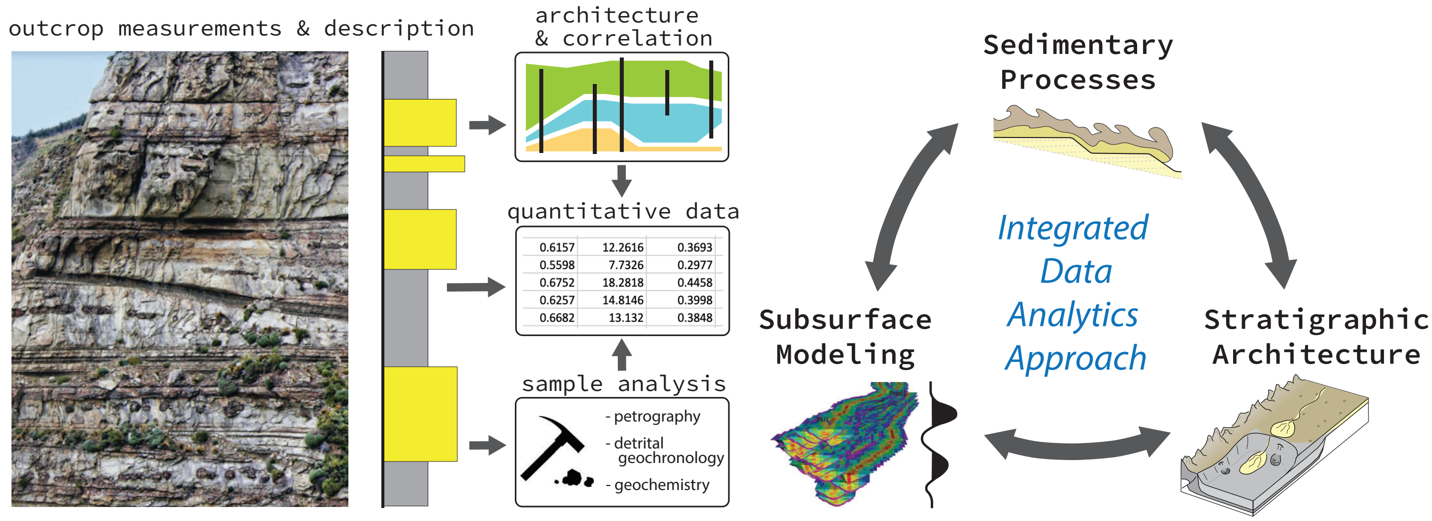

Figure 1: CSS research themes and applications emphasize an integrated approach.

Our mission is accomplished through three main investigative **THEMES,** with a common foundation in an integrated data analytics approach (Fig.1).

Sedimentary Processes

CSS is built on a foundation of exceptional outcrops, which we examine to deduce fundamental sedimentary processes, ranging from grain-scale transport to source-to-sink functioning (Fig. 2). These analyses are supported by relevant boundary conditions such as basin history, tectonics, climate, and sediment-routing system configuration, providing important context for exploration-scale models and play concepts. We refine models of how processes lead to stratigraphic products and show the connection to improved characterization and prediction of the subsurface (Figs. 3 and 4). Research results from this theme provides the critical bed-scale input into our database and stratigraphic architecture models, which are the foundation for our subsurface modeling work.

Stratigraphic Architecture

Analysis of stratigraphic architecture has proven critical for building reservoir analogs (Fig. 3). Our focus on the linkage of sedimentary processes to stratigraphic architecture allows us to formulate conceptual and statistical bed-, reservoir-, and basin-scale stratigraphic models for: (1) shelf-to-slope sediment transfer; and (2) predictions of reservoir distribution and architecture. This theme is a critical link between our bed-scale analyses and our applied outcrop-based geomodels and data analytics, the learnings from which represent some of our most impactful contributions based on sponsor feedback. Our emphasis on thorough and consistent documentation of stratigraphic architecture promotes robust spatial-temporal comparisons within and among the slope depositional systems we analyze, from shelf to basin floor. Stratigraphic architecture analysis is the foundation for quantitative workflows in our subsurface modeling research.

Subsurface Modeling

We investigate the impact that bed- through field-scale stratigraphic architecture has on connectivity, fluid flow, and seismic-reflectivity, providing guidance for incorporation of critical geological characteristics in models (Fig. 3). Our research is aimed at understanding if and when subsurface models accurately predict reservoir architecture and behavior. We combine flow simulation, forward seismic modeling, and machine learning with fine-scale outcrop architectural models to answer these questions. Our work bridges a gap between outcrop and subsurface by leveraging our growing database and creating quantitative pathways to connect analog knowledge and data to reservoir prediction (Fig. 4). Subsurface modeling studies are grounded by observations and interpretations of sedimentary processes and stratigraphic architecture. Additionally, our modeling inspires new questions that motivate renewed field-based investigations.

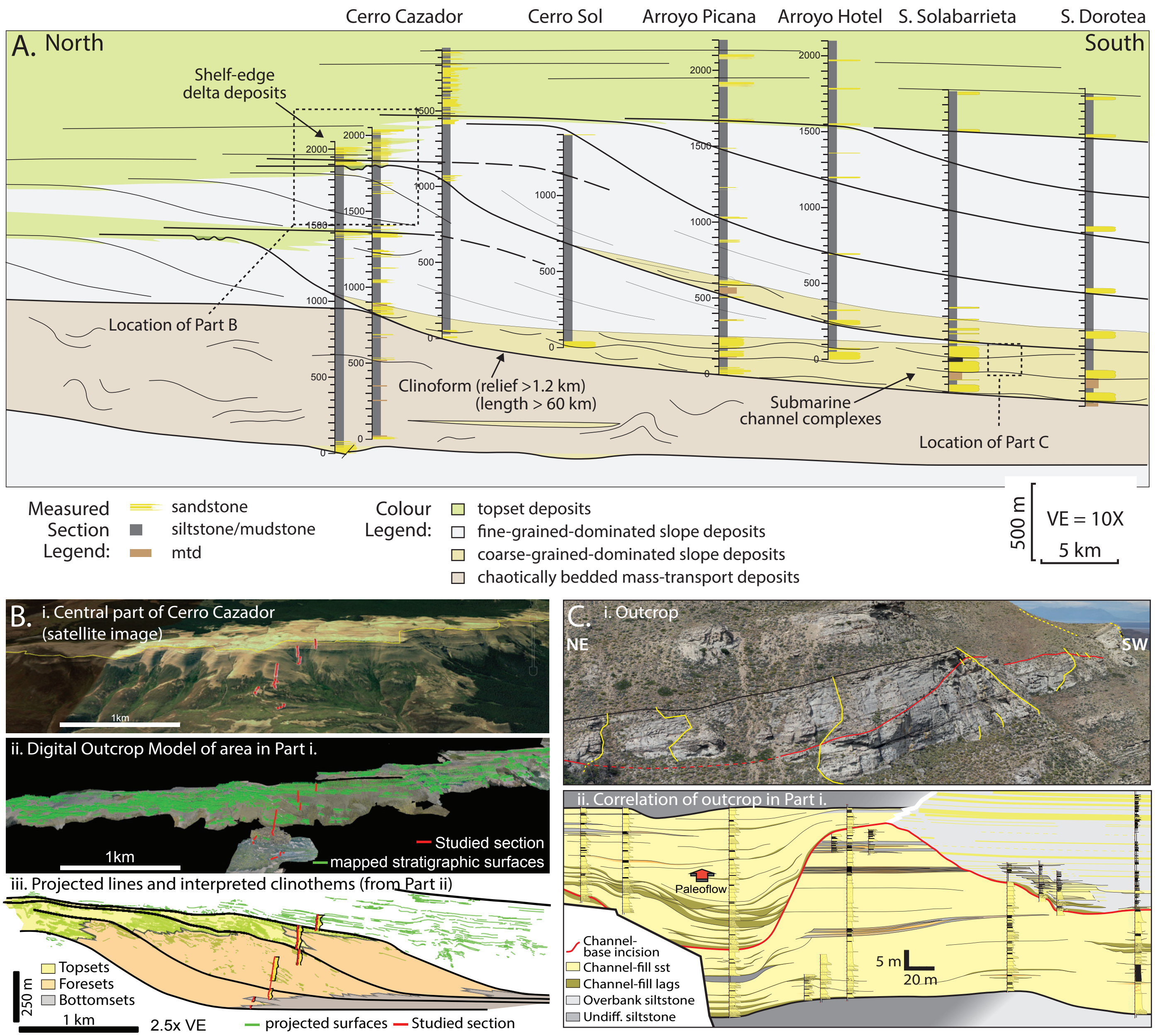

Figure 2: Seismic-scale stratigraphic context for the Tres Pasos Formation (part A) is the foundation for focused studies on depositional system deposits from the shelf (part B) to submarine slope channels (part C).

<u>Project History and Previous Research Products</u>: The stratigraphy of deep-water outcrops in the Magallanes Basin, southern Chile, has been studied for decades 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 in the 2000s. The earliest iteration of the Chile Slope Systems JIP started in 2007 at the University of Calgary, which grew into a multi-university effort in 2012 (officially Phase 1). To date, the project has benefited from the support and collaboration of 15 companies.

Our redesigned website provides access to all research products, including outcomes from all previous phases. The website hosts a wealth of fundamental outcrop data (e.g., measured sections, stratigraphic correlations, drone-acquired photogrammetry models) and our new database (e.g., measured section data including grain size, facies, bed thicknesses, etc.). Our analyses have led to numerous scientific and applied outcomes including: (1) refined conceptual sedimentaryprocess models to explain slope channel-fill patterns (e.g., Hubbard et al., 2014, 2020; Englert et al., 2021); (2) enhanced regional-scale correlations and sediment-routing characteristics in deep-water basins (e.g., Daniels et al., 2018; Englert et al., 2018; Auchter et al., 2020; Bauer et al., 2020). (3) documentation and interpretation of reservoir-scale slope channel stacking patterns (e.g., Pemberton et al., 2016; Reimchen et al., 2016); (4) quantified impact of stacking patterns and internal architecture on connectivity and seismic responses for channelized reservoir strata (e.g., Jackson et al., 2019; Meirovitz et al., 2021; Reutten, 2021; Langenkamp, 2021); and (5) application of advanced analytical techniques to subsurface prediction of subsurface architecture (e.g., Vento, 2020). Our previous phases have supported the research of 12 M.S. students, 7 Ph.D. candidates, 4 post-doctoral fellows, and the 3 principal investigators. Research results have been delivered in a timely manner through annual consortium meetings and field workshops, site visits, and on-line (http://www.chileslopesystems.com).

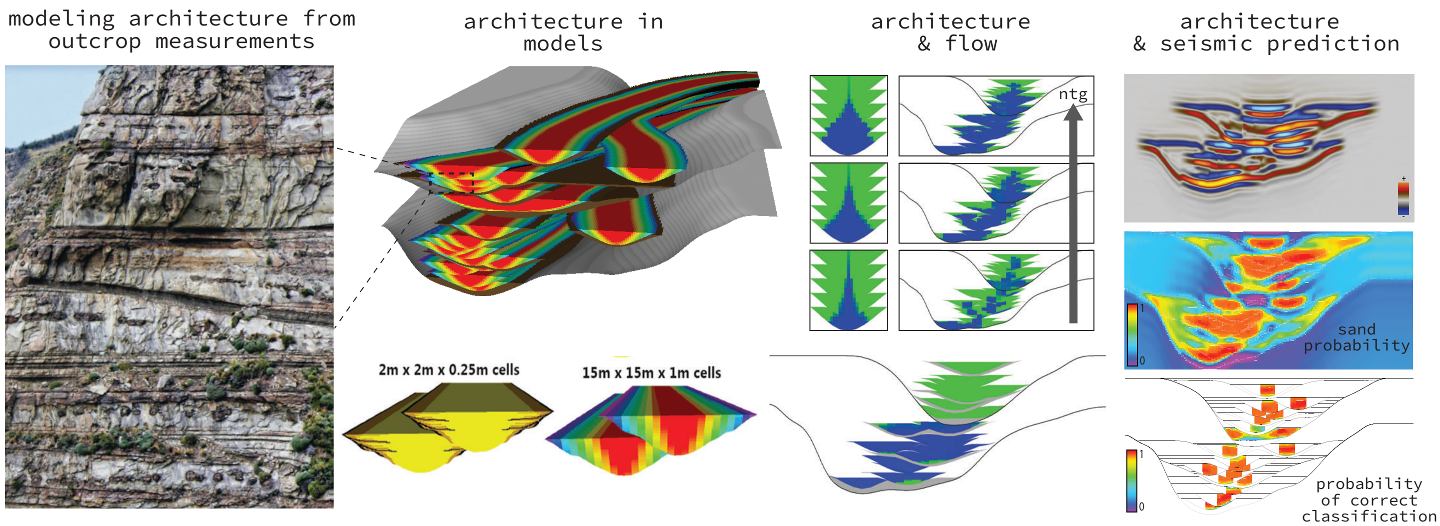

Figure 3: Outcrop to subsurface analog modeling approaches.

Field Areas and Datasets:

Exceptional outcrop belts are the foundation of the CSS project. The Magallanes Basin of Chile has been a focus since the JIP inception, while the Nanaimo Group of British Columbia was added as a focus at the onset of Phase 3. We emphasize outcrops that are analogous to continental-margin systems where our sponsors are actively exploring, and this motivates consideration of other world-class outcrop belts going forward.

The **Upper Cretaceous Magallanes Basin of southern Chile** contains >4 km of deep-marine strata, including several coarse-grained units that record turbidite depositional system evolution (Fig. 2). The unique tectonic history of this basin has resulted in a regionally continuous outcrop belt that features numerous distinct phases of deep-water stratigraphic architecture evolution. Channel-levee complexes and basin plain units of the Cerro Toro Formation; basin-wide mass-failure dominated stratigraphy with ponded slope fans that record a major shift in sedimentation; and high-relief slope systems on the order of >1 km high (paleobathymetric relief) and at least 60 km long (from shelf to lower slope) of the Tres Pasos Formation. These high-relief slope systems have been the principal focus of CSS Phases 1-3, including the deposits of stacked channel complexes up to 300 m thick that have been used as analogs to reservoirs around the globe (Fig. 2C). These slope channel strata are directly correlated to coeval exposures of shelf and shelf-edge deposits (Fig. 2B), offering opportunities to constrain shelf-slope sediment partitioning and associated controls. The mapping and chronostratigraphic work from previous phases (Fig. 2A) provides seismic-scale constraint on basin-filling patterns, and exceptional context within which to investigate detailed, reservoir-scale architecture.

The similarly aged **Nanaimo Group of Vancouver Island** and adjacent areas in western British Columbia, Canada, includes 2-3 km of deep-water slope stratigraphy exposed in a 160 km-long, strike-oriented transect. Seismic-scale slope channel systems, as well as the deposits of channel-lobe transition zones and submarine fan lobes are widespread. Exceptionally well-preserved bedforms have been identified in a variety of these settings that are linked to flow transitions, which provide important insight into channel and lobe sedimentary processes and products. The world-class deep-water outcrops record uplift and denudation of a volcanic arc immediately to the east of the study area, yet their sedimentology has been largely overlooked until the last half-decade. An established chronostratigraphic framework for the basin provides the foundation for planned CSS research. Our success with branching out to these outcrops motivates consideration of **additional outcrops and data sources**, based on sponsor feedback and interaction.

Data from each field area is collected, drafted, digitized, and transferred into our growing relational database (CSS_DB). This raw data provides the inputs to calculate a suite of descriptive statistics that capture characteristics of grain-size and bedding at various architectural scales. These data form the basis and ideation for subsurface studies that directly link the power of analog data to improving subsurface prediction. In these workflows we translate raw data into interpreted architecture that is directly demonstrated in models. The end product produces models that translate field data, observations and interpretation into a tangible, testable, and shareable form. We believe that our high standards of consistent field data collection creates a **clean, robust, and reliable database** that is ideal for development and testing of machine learning and related techniques (Fig. 4).

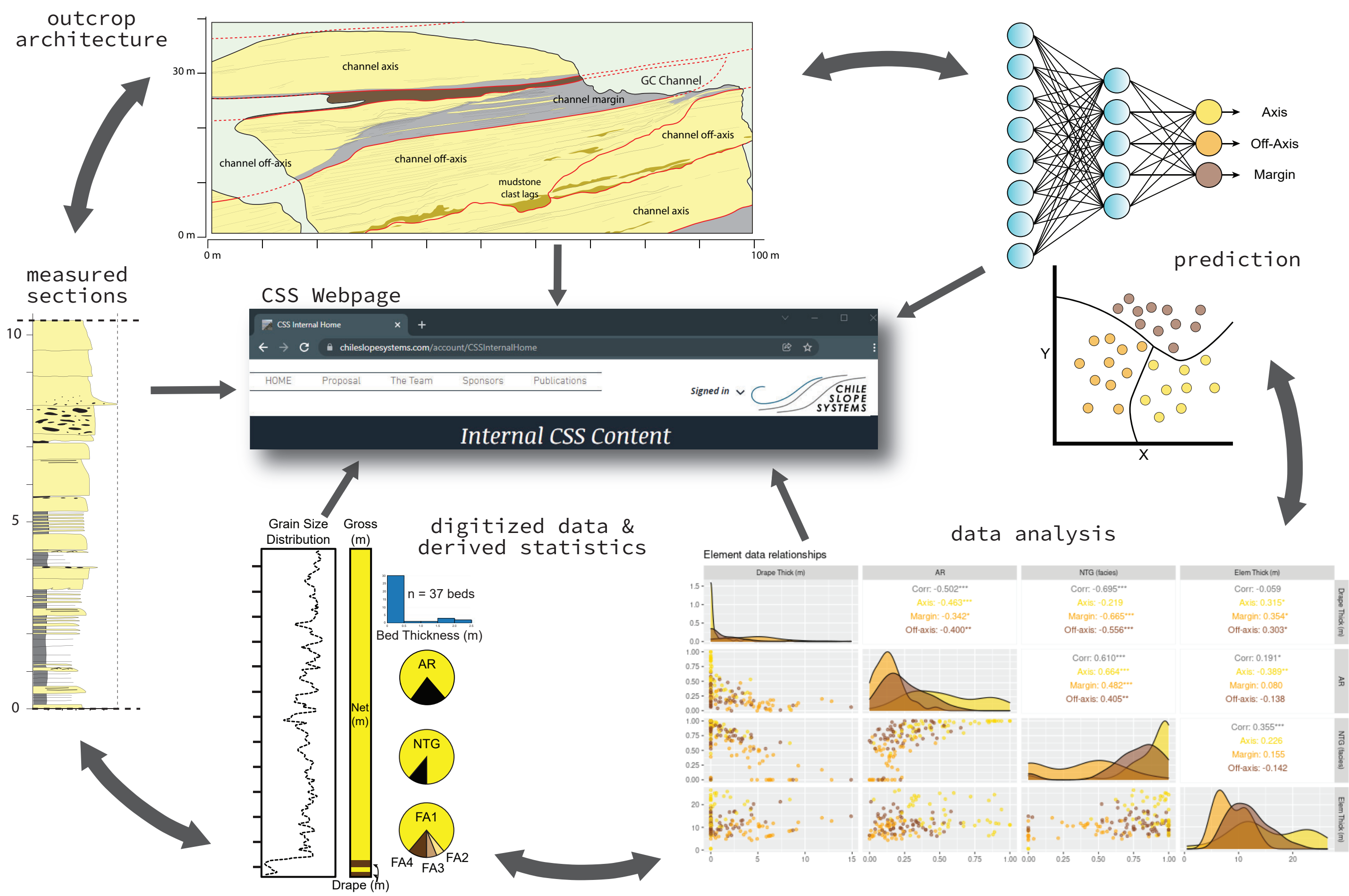

Figure 4: Integrated outcrop-to-data analytics and prediction delivered via new website and database.

Phase 4 Research Plan and Trajectory:

This proposal outlines the rationale and plans for a fourth three-year phase to begin in July 2022. Our three thematic areas frame the design and implementation of our research plans for Phase 4 (Fig. 1). Table 1 communicates our proposed initiatives and projects for Phase 4 via key questions, how we propose to address those questions, and anticipated outcomes. Our proposed research combines new outcrop data collection, integration and synthesis of data collected in previous phases, reservoir and forward-seismic modeling, and leveraging our robust and increasingly growing digital database (CSS_DB) for data analytics. Studies will be accomplished through the collective effort of students, post-docs, and principal investigators, with feedback and ideas from active sponsors.

Table 1: Proposed research questions and anticipated impacts for Phase 4.

Key questions	How we will answer	Anticipated impact(s)
Sedimentary Processes and Stratigraphic Architecture		
How do geomorphic features like **knickpoints**, **bedforms**, and **sinuous channel bends** shape submarine channel fills? What are the implications on sand deposition and overall deposit architecture?	Analyze identified outcrops in Nanaimo Group at Mayne Island and Figueroa clinothem at Alvarez ridge, Chile	Constraints on submarine channel deposit heterogeneity, connectivity, and trapping longitudinally.
How does **grain size** in channelized deposits vary longitudinally at the slope system scale? Can grain-size metrics from a large database of outcrop sections predict system-scale architectural trends?	Compute descriptive statistics of grain size from >10k m of digitized measured sections in CSS_DB. Analyze slope-system-scale trends in grain-size metrics via proximal-distal transects in the Figueroa and Puma (Chile) clinothem systems.	Development of: (1) slope-system-scale conceptual model linking grain-size trends to well-constrained architecture to improve prediction; (2) analogue insight into prospective channel systems 10s of km long in prospective basins.
How does sedimentological evidence for **bypass** differ as a function of slope scale and relief? For example, how do turbidite deposits on prodeltaic slopes differ from basin-margin-scale slopes?	Sedimentologically investigate deltaic through upper slope strata at Cerro Cazador (Chile) and identify complementary outcrops in North America as basis for comparison.	Add to our extensive library of outcrop analogs of slope systems. Target data collection for improved reservoir characterization (e.g., model inputs and associated uncertainty).
What is the spatial and temporal variability of **point sources of coarse-grained sediment** to deep-water basins? How does deep-water deposition relate to basin-margin topography and external forcings?	Analyze maximum depositional ages and provenance trends from U-Pb detrital zircon data from multiple sites across >150 km longitudinal distance spanning Cerro Toro, Tres Pasos, and Dorotea Fm depositional phases.	Improved knowledge of basin-scale configuration of slope systems and coarse-grained fairways and their relationship to external forcings.
Stratigraphic Architecture		
What are the sedimentological and architectural relationships of **shelf-edge and upper-slope stratigraphic traps**? What sedimentological and stratigraphic characteristics of the shelf segment improve prediction of slope facies and architecture?	Characterize outcrops of prodeltaic, shelf-edge, and upper-slope strata on Cerro Cazador (Chile) and potential other outcrops or data sets.	Characterization of the shelf edge zone (connecting prodeltaic to upper-slope segments) will provide a tangible analog for the commonly asked question regarding up-dip traps.
How is sediment transferred and distributed across **clinoforms** in space and time? What is the nature of sediment **bypass** as a function of slope system gradient/depth/type?	Synthesize data from previous and proposed CSS work, and compare with data from other systems.	Improved conceptual models of stratal architecture across slopes, from shelf to basin floor.
How do bed-scale facies and architectural heterogeneities vary in different **slope depositional environments** (e.g., channel fills, channel-lobe transition zones, intra-slope basins)?	Work with sponsors to identify gaps in our database/outcrop library. Synthesize current data and identify new outcrops or data sets.	Add to our extensive library of outcrop analogs of slope systems. Target data collection for improved reservoir characterization (e.g., model inputs and associated uncertainty).
How does **sedimentary texture** (grain size and shape, sorting, matrix proportion, etc.) in channelized sandstones vary as a function of stratigraphic architecture and slope position?	Collect samples from intervals that are well constrained architecturally (from Chile and Nanaimo outcrops and potentially from other systems). Conduct petrographic analyses to quantify textural characteristics and integrate with stratigraphic framework.	Existing predictive models of intra-channel-fill heterogeneity will be enhanced with micro (textural) information. Findings will also inform interpretation of sediment-gravity-flow processes.
What is the influence of syn-sedimentary deformation on **intra-slope basin** stratigraphic architecture?	Integrate and synthesize data collected in the latter part of Phase 3 from El Chingue Bluff (Chile).	Bed-scale facies and architectural characterization linked to mapped characteristics (orientation, offset, etc.) of syn-depositional normal faults in intra-slope fan systems. Quantification of bed pinch-outs.
Can we predict facies distributions and geologic features directly from photogrammetry models?	Adapt automated analysis and classification using Machine Learning algorithms from well-established remote sensing techniques.	Prediction data capturing detailed facies distribution (e.g., net to gross ratios) and geologic features (e.g., architectural elements, fine-medium scale sedimentary structures).

Key question	**How we will answer**	**Anticipated impact(s)**
Subsurface Modeling		
Can we **mine data** from photogrammetric point clouds to provide valuable metrics and statistics for modeling and machine learning workflows?	Utilize classified photogrammetry models that delineate facies and geologic features and quantify results in CSS_DB.	Architectural constraints for machine learning methods (e.g., transition probabilities, distributions of widths and thicknesses).
What is the hierarchy of **non-reservoir deposits** and how do they influence reservoir distribution and connectivity?	Analyze database and outcrop photogrammetry model for relationships between reservoir and non-reservoir reservoir deposits.	Predictive models of architectural distribution including how, when, and why deep-water channel reservoirs are compartmentalized at varying scales and how to include these architectural data into geomodels.
How does our evolving understanding of **intrachannel architecture** impact storage and flow along channel length and between channel bodies?	Leverage recent detailed outcrop work and statistics regarding bed-scale architecture and fill evolution of channel elements (e.g. Alvarez Ridge) to build bed- to geobody-scale models	Demonstrate the link between sedimentologic observations and recent research results and subsurface impact, including whether this intra-geobody architecture impacts fluid storage and flow.
How is architectural information preserved in filtered data (logs, seismic, production)? How can **machine learning (ML)** approaches be designed to better predict architecture?	Use measured section data in CSS_DB to test the connection between data and filtered subsurface responses (forward modeling), and filtered subsurface responses and computer prediction (inverse modeling), while bounded by architectural constraints.	Optimized workflows and tests to guide architectural machine learning (ML) predictions with seismic and well data.
What workflows can be designed to generate more realistic **subsurface models** that are "smart" interpretation- and architecture-driven rather than data-driven?	Using CSS_DB, test machine learning workflows using a hierarchical approach: 1D (core/well log data), stochastic 2D near-wellbore models with architectural statistics, and then extrapolated between near-wellbore models to 3D constrained to seismic data.	Hierarchical modeling workflows that honors data constraints and generates equiprobable architecturally realistic models.

Research Products and Sponsor Benefits:

- Immediate access to all research results through our newly designed password-protected web-interface (http://www.chileslopesystems.com). These include:
  - Recently launched web-enabled database of statistical compilations of field data (CSS_DB)
  - Measured section data (Illustrator files/PDF, correlation panels, raw data files)
  - Matlab/Python/R scripts
  - 3-D architectural models (Petrel projects),
  - posters, presentations, videos, and reports/papers
- 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 areas. We provide annual field courses in Chile (temporarily suspended for 2021 and 2022), and similar trips to British Columbia as requested. We will consult with sponsors to identify preferred field trip strategies, especially in light of ongoing public health measures.
  - We typically hold a one-day meeting associated with the timing/location of the annual AAPG Meeting to deliver findings from the previous year and discuss ongoing and future research activities. During the pandemic, we have pivoted to an online platform for these meetings with dedicated one-on-one time with each company.
- Companies will receive an annual progress update of findings highlighting the results of the JIP. We plan to resume PI visits to offices when safe to do so.
- Opportunities to interact with PIs and students at additional, company-specific site visits (in-person or virtual): topical seminars, asset reviews, etc.
- Companies will be acknowledged on all disseminated material.

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Joint Industry Project

Consortium Terms

Models and Predictions of Slope System Reservoirs

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 (2022-2025), option to opt out of the agreement at the conclusion of each project year

- ☑ *Financial Contribution:* $47,500 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
  - Immediate access to all research results through password-protected web-interface including database of field data (CSS_DB), 3-D architectural models (Petrel projects), measured section data (Illustrator/PDF files, correlation panels, raw data files), statistical analyses and prediction methods (Matlab/Python/R scripts) using CSS_DB, posters, presentations, videos, and reports/papers.
  - Annual scientific and financial progress report presented at annual consortium meeting, as well as digital data delivery at end of project.

- ☑ *Annual 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

- ☑ Opportunities to interact with PIs and students at additional, company-specific site meetings (arranged annually)

- ☑ *Recognition:* Sponsors will be acknowledged on all disseminated material