CHILE SLOPE SYSTEMS

University of Calgary
Colorado State University
Universitat Autònoma de Barcelona
Virginia Tech

JOINT INDUSTRY PROJECT

Chile Slope Systems Phase 5 (2025-2028): MODELS AND PREDICTIONS OF SHELF-SLOPE SYSTEM RESERVOIRS

Project Mission: We develop predictive stratigraphic models of submarine slope systems (including linked shelf-edge to upper slope segments) from world-class outcrops, using qualitative and quantitative analysis of sedimentary processes and deposits to improve reservoir predictions and test impacts on reservoir performance.

Summary of Proposed Research: CSS Phase 5 will build on Phases 1-4 (2012-2025) with a continued focus on exceptional outcrops and their relevance to subsurface characterization and prediction. We plan to enhance our portfolio of outcrop-analog information in the next phase with a focus on the linked shelf-edge to upper slope segments. We will continue to work in the Magallanes Basin (Chile), as well as explore other world-class outcrop belts (e.g. Ainsa Basin, Spain) and subsurface datasets. Specific research questions, our unique approach to finding answers, and anticipated impacts of our proposed Phase 5 research are outlined in Table 1. Access to our website and our comprehensive database of research products is available to sponsors with login information provided. Prospective sponsors can access a limited preview of the web content (http://www.chileslopesystems.com/guestaccess).

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. A major achievement and deliverable made available to sponsors in CSS Phase 4 was our digital database (CSS_DB), which includes data from all previous phases of research and exemplifies our cross-cutting ***Integrated Data Analytics Approach*** (Fig.1). The foundations of CSS_DB are outcrop measurements, capturing 100s of thousands of robust and consistently collected data points that are, collectively, the foundation for ongoing and proposed quantitative analytics efforts (e.g., statistical analysis of the multi-scale shelf-edge to slope depositional architecture, and subsequent machine learning prediction of that architecture from 1-D data). These data are hosted on an interactive, web-driven platform that is contextually linked to supporting literature (e.g., presentations, papers, and field guides), providing outcrop data for direct comparison to complement affiliate datasets.

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

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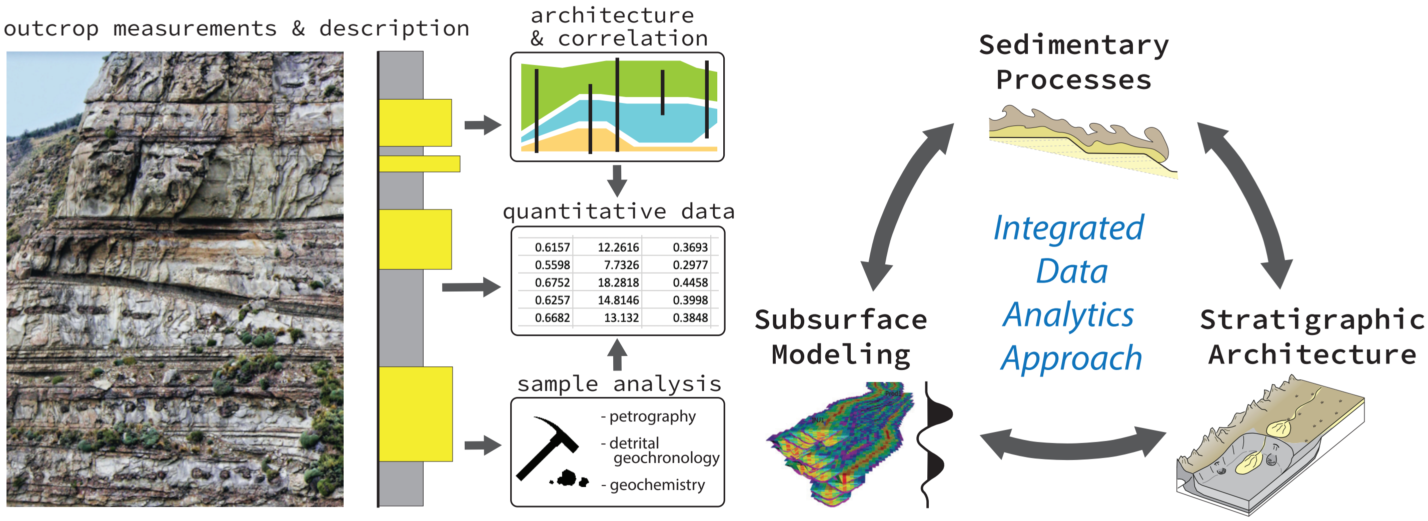

Figure 1: CSS research themes and applications emphasize an integrated approach.

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 in detail to deduce fundamental sedimentary processes, ranging from grain-scale transport to source-to-sink reconstructions (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 reservoir characterization and prediction (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; (2) predictions of reservoir distribution and architecture; and (3) architectural controls on factors such as trapping and seal style. 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, by integrating photogrammetric techniques and digital outcrop modeling, promotes robust spatial-temporal comparisons within and among the deep-water 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 basin-scale stratigraphic architecture has on reservoir distribution, connectivity, and fluid flow (intra-reservoir baffles/barriers and system trap/seal), and their interpretability from seismic-reflection data (Fig. 3). Our research is aimed at providing insight and guidance into how reservoir- to basin-scale architecture impacts subsurface geocellular model prediction. We use outcrop architectural models to generate flow simulation, forward seismic, and machine learning models to answer these questions. Our work bridges the gap between outcrop and subsurface by leveraging our database and creating quantitative pathways to connect analog knowledge to development- and exploration-scale prediction (Fig. 4). Additionally, our modeling inspires new questions that motivate renewed field-based investigations.

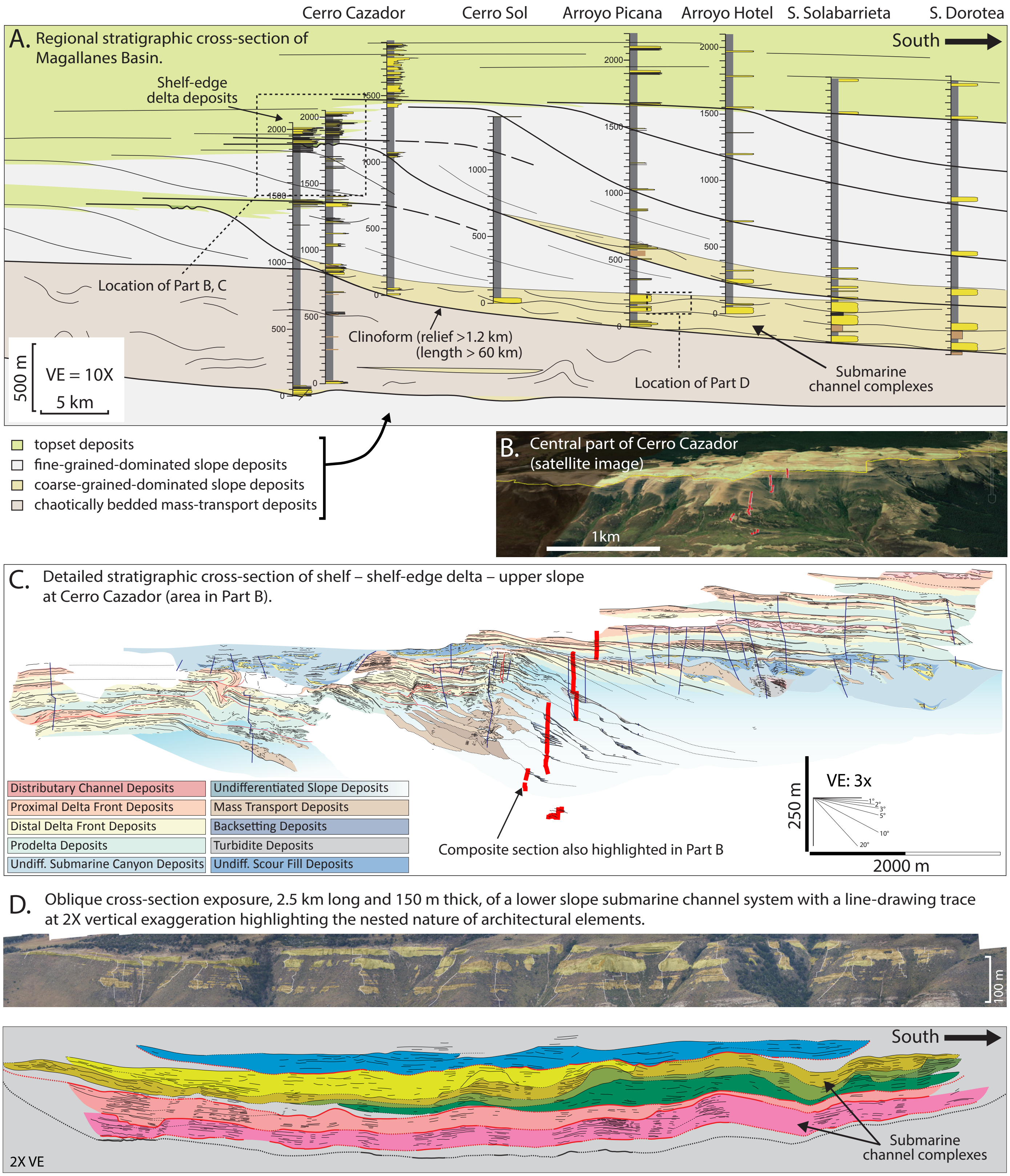

Figure 2: Seismic-scale stratigraphic context for the Tres Pasos and Dorotea formations (part A) is the foundation for focused studies on depositional system deposits from the shelf (part B-C) to submarine slope channels (part D).

Project History and Previous Research Projects: 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 three principal investigators from Phases 1-4 gained expertise in the region as Ph.D. students with the Stanford Project on Deep-water Depositional Systems in the 2000s. Dr. Miquel Poyatos Moré joined CSS in the field starting in 2020 as a research collaborator and is a principal investigator for this Phase 5 proposal. 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 (CSS Phase 1). To date, the project has benefited from the support and collaboration of more than 15 different companies.

Our website went through a major redesign in Phase 4 and provides access to all research products, including outcomes from all previous phases. The website hosts a wealth of fundamental outcrop data (e.g., measured sedimentary logs and stratigraphic correlations) as well as our 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 sedimentary-process models to explain slope channel-fill patterns (e.g., Hubbard et al., 2014, 2020; Englert et al., 2021, 2023; Puckett, 2024; Jobe et al., 2024) (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; Coutts et al., 2024). (3) documentation and interpretation of reservoir-scale slope channel stacking patterns (e.g., Pemberton et al., 2016; Reimchen et al., 2016; Daniels et al., 2024; Kaempfe-Droguett et al., 2024); (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; Ronnau, 2024; La Marca et al., 2024; 2025). 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 our website (http://www.chileslopesystems.com).

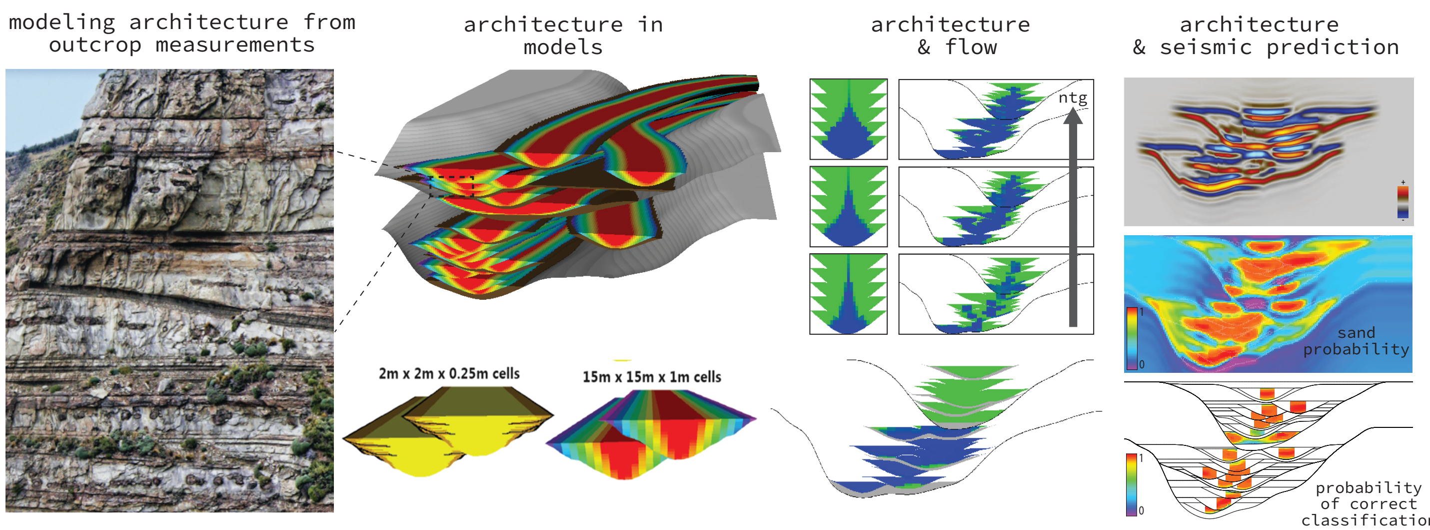

Figure 3: Outcrop to subsurface analog modeling approaches.

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 we continually consider other outcrop localities to answer pointed problems (e.g., Phase 3-4 investigations in the Cretaceous Nanaimo Group, British Columbia). In Phase 5, we will introduce outcrops from the Ainsa Basin (Spanish Pyrenees) to our portfolio. 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 Magallanes Basin's unique tectonic history has resulted in a regionally continuous outcrop belt featuring 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 shelf-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 1-4, 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-edge and shelf deposits (Dorotea Formation, Fig. 2B), offering opportunities to constrain shelf-slope sediment partitioning and associated controls. The mapping and chronostratigraphic work from previous phases (Fig. 2A) provides exploration-scale constraint on basin-filling patterns, and exceptional context within which to investigate detailed, reservoir-scale architecture.

The **Eocene Aínsa Basin** is part of the South Pyrenean Foreland, in northern Spain. The basin fill is characterized by a 4-5 km-thick succession dominated by deep-water slope deposits (Hecho Group) followed by a deltaic clinoform succession (Sobrarbe Formation) and finally by continental deposits (Escanilla Formation). The slope deposits comprise a series of channelized/lobate sandstone bodies, contained within a thick mud-rich heterolithic succession. Sediment routing systems were affected by a bathymetrically complex seabed topography, created by the coeval growth and propagation of submarine thrusts and folds, and by the emplacement of mass-transport deposits (MTDs). The outcrop belt of the Aínsa slope systems is exposed along a SE-NW direction, parallel to regional palaeoflow, and pass to coeval channel-lobe transition and basin-floor deposits in the adjacent Jaca Basin. The overlying deposits of the Sobrarbe Formation display a seismic-scale (up to 300 m-thick) clinoform succession and offer the possibility to be compared with ongoing work in the clinoform systems in the Magallanes Basin.

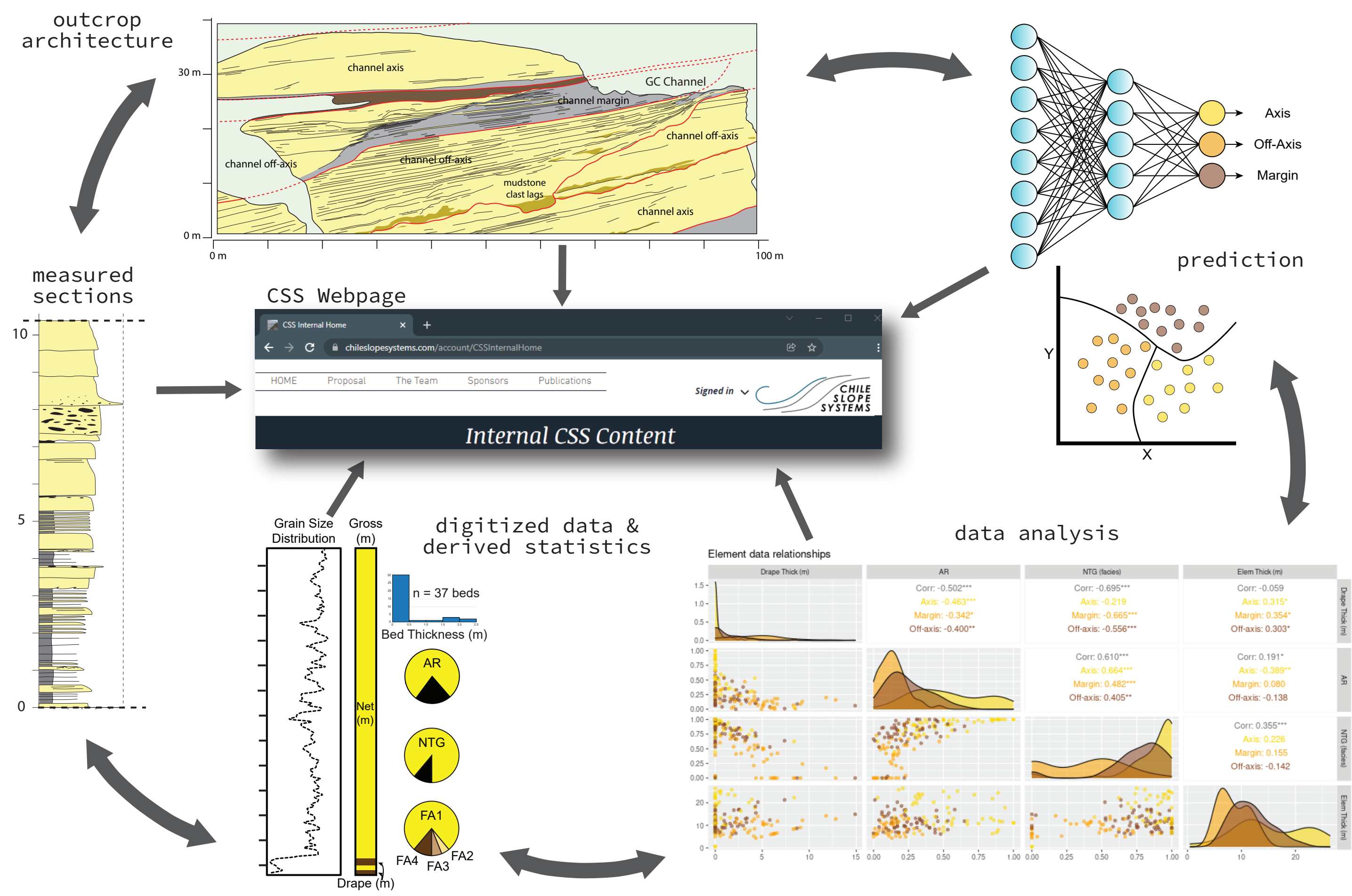

Figure 4: Integrated outcrop-to-data analytics and prediction delivered via new website and database.

Data from each field area is collected, digitized, and stored in our relational database (CSS_DB), launched in Phase 4. This raw data is framed within a robust and consistent interpretive architectural framework and used to calculate descriptive statistics on grain-size and bedding characteristics within and across architectural scales. These data form the basis and ideation for subsurface demonstration studies that directly link the power of analog data to informed subsurface prediction translating field data into tangible, testable, and shareable products. Our rigorous data collection and digitization standards ensure a **clean, robust, and reliable database** ideal for developing and testing machine learning techniques (Fig. 4).

Phase 5 Research Plan and Trajectory: Our three thematic areas (Fig. 1) frame the design and implementation of our research plans for Phase 5. Table 1 communicates our proposed initiatives and projects for Phase 5 via key questions, how we propose to address those questions, and anticipated impacts and value. 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 ever-growing database (CSS_DB) for data analytics. A notable new initiative and growth area for Phase 5 is additional focus on the topset area of the clinoform succession, formed by shallow-marine and deltaic strata, and their link to slope clastic systems, as well as comparison studies with other field areas (e.g., Ainsa Basin). Our proposed studies will be accomplished through the collective effort of students, post-docs, and principal investigators, with feedback and ideas from active sponsors.

Research Products and Sponsor Benefits:

- Access to all research results through our newly designed password-protected web-interface (http://www.chileslopesystems.com). These include:
  - Web-enabled relational database of statistical compilations of field data (CSS_DB)
  - Measured section data (Illustrator files/PDF, correlation panels, tabulated data, etc.)
  - 3-D architectural models (Petrel projects)
  - Posters, presentations, videos, and reports/papers
  - Scripts (Matlab, Python, R) used for data processing available upon request
- Opportunities for interaction with PIs, post-docs, 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 and similar trips to other outcrop locations (e.g., British Columbia, Spanish Pyrenees) as requested.
  - Webinars and other online/virtual interactions that are either organized by us to communicate new results or requested by sponsors. (For example, during Phase 4 we led a two-hour seminar and discussion about shelf-edge architecture and trapping styles with a sponsor company interested in that topic.)
  - We can also make plans to visit in-person or virtually for meetings to present our latest work, provide feedback, and develop ideas about how to optimize our work to best fit sponsor needs.
- Companies will be acknowledged on all disseminated material.

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Key question	How we will answer	Anticipated impact(s)
Sedimentary Processes / Stratigraphic Architecture		
What are the geometries and facies relationships of **stratigraphic pinch-outs** and **remobilized strata** in the shelf-edge to upper-slope transition zone?	Field and sample-based quantitative, geometric and stratigraphic characterization of different examples complemented with interpretation from photogrammetric models.	Classification of the different styles of stratigraphic pinch-outs and mass wasting / remobilization deposits in shelf-edge to upper-slope settings, for comparison with other outcrop / subsurface datasets.
What is the stratigraphic expression of the **updip to downdip transition** from shelf-incised canyons to slope channels?	Field-based characterization of erosional / depositional elements and indicators of sediment bypass along the updip expression of clinoform surfaces.	Set of criteria to recognize evidence and predict for large-scale sediment bypass in shelf-edge to upper-slope settings, and their link to coarse-grained sediment delivery downslope.
What are the facies and architectural differences between **river-** and **marine-dominated topset strata**?	Measurement and correlation of several large-scale stratigraphic logs including the topset part of the clinoform succession. Line drawings of outcrop geometries for architectural characterization of depositional elements.	(1) Set of criteria to differentiate between different strata in the topset segment of the Magallanes clinoforms. (2) Conceptual models of different topset styles according to dominant process regime.
How are shelf-to-slope stratigraphic patterns expressed as a function of **different scales of clinoforms** (e.g., basin-margin, intrashelf, deltaic)?	Refine regional stratigraphic cross section from shelf and shelf-edge (Dorotea Formation) to slope (Tres Pasos Formation) strata at scale of >50 km proximal-distal distance and ~3 km total stratigraphic thickness.	(1) Improved characterization of multiple scales of clinoform systems; (2) better linkage of shelf-to-slope segments important for constraining updip trapping styles; (3) more accurate stratigraphic template for synthetic seismic modeling.
How does **grain-scale texture** (e.g. size, shape, sorting), framework grain **mineralogy**, **matrix abundance,** and **organic matter abundance/type** in sandstones relate to architecture and depositional system characteristics?	Collect samples from representative facies within our well-constrained architectural framework and conduct micro-scale characterization. (Continuation of a Phase 4 study that investigated size/sorting for a common slope-channel facies.)	Information valuable for (1) reservoir quality prediction in analogous depositional architecture and (2) insights into grain-scale sedimentary processes.
How does **grain size** of channel-fill deposits vary longitudinally at the scale of the slope system? Can grain size data from a **large database** of outcrop measured sections predict architectural trends?	Compute descriptive statistics of field-observed grain size from >15 km of digitized measured sections in CSS_DB. Analyze slope-system-scale trends and compare to known stratigraphic architecture.	Development of: (1) slope-system-scale conceptual models linking grain-size trends to well-constrained architecture; (2) analog insight into channel systems 10s of km long in prospective basins.; (3) Serves as an example of how to leverage CSS_DB for 'exploration-scale' questions.
Are there additional **slope channel recognition criteria** that validate models and leverage our database (e.g. mudstone intraclast characteristics, scour-fills and canyon deposits)?	Characterization of outcrops How do and distribution within a slope channel-fill relate to channel-fill styles, dimensions, and stacking patterns? … and/or investigate from the DB side (e.g., correlation with A-OA-M	Improved conceptual models of stratal architecture across slope channel systems.

How do the **Ainsa Basin slope and shelf-edge systems** compare to the architectural models developed from the Magallanes Basin?	Comparison of different elements of the Ainsa Basin succession with the Magallanes clinoforms (e.g. dominant processes, facies proportions, slope channels, mass-wasting deposits).	Conceptual models of clinoform development and scaling relationships of slope channel systems in tectonically-active (foreland) basin margins.
What are the main controls (allogenic vs autogenic) on **channel planform location and stratigraphic stacking** (depositional system to basin scale).	Mapping of channel systems with respect to the main tectonic structures in the Magallanes Basin.	Refined understanding of vertical versus horizontal stacking, enabling enhanced predictive capability in subsurface analogs.
Outcrop to Subsurface Translation: Modeling		
Are there key **seismic reflector characteristics** that the diverse up-dip slope to shelf pinch-outs exhibit?	Simple seismic modeling of shelf-slope transition with variable rock properties.	A library of simple model predictions that demonstrate the seismic response of different styles of shelf pinch-outs.
How is **multi-scale shelf-slope architecture** expressed in seismic reflectivity data?	Build simple hierarchical geometric models and forward seismic model.	Forward seismic models at different scales and resolutions of analog data for subsurface comparison.
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 bound by architectural constraints.	Optimized workflows and tests to guide architectural machine learning (ML) predictions with seismic and well data.
How can we **leverage predictions** of facies distributions and geologic features **from photogrammetry models**?	Use developed methods in Phase 4 for unsupervised classification and supervised calibration with measured sections (on the ground observations).	Additional data and measurements from outcrop to build spatial relationships, trends, and modeling statistics.
Can we **mine data** from photogrammetric point clouds to provide **valuable metrics and statistics** for modeling and machine learning workflows?	Classification of lithologies from outcrop models to support measurement of length scales, geometries, proportions, and lateral/vertical facies transitions.	Architectural constraints for machine learning methods (e.g., transition probabilities, distributions of widths and thicknesses).
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.
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.

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, Miquel Poyatos-More, Universitat Autonoma de Barcelona

- ☑ *Term of Agreement:* 3 years (2025-2028), option to opt out of the agreement at the conclusion of each project year

- ☑ *Financial Contribution:* $60,000 USD/year/per sponsor, which includes 40% 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