University of Calgary
Virginia Tech
Colorado State University

JOINT INDUSTRY PROJECT

CSS Phase 3 (2019-2022):
Architectural Analysis and Modeling of Slope Reservoirs

Project Mission: We analyze world-class deep-water outcrops to develop predictive models of slope systems from reservoir to exploration scales, and test the impact of observed stratigraphy on fluid flow connectivity and seismic response. We present interdisciplinary approaches to solve problems associated with reservoir characterization, prediction, and modeling, while providing educational opportunities for our sponsors.

Our mission is accomplished through three main investigative themes:

THEME 1: Quantitative, Conceptual, and Architectural Models of Slope Stratigraphy

CSS is built on a foundation of exceptional outcrops, which we use to formulate conceptual bed-, reservoir-, and basin-scale sedimentologic and stratigraphic models for: (1) shelf to deep-water sediment transfer; and (2) predictions of reservoir distribution and architecture. Our work leverages a vast database of stratigraphic information for statistical analysis, which we use in quantitative workflows in our geomodeling research (Fig. 1).

THEME 2: Geomodeling, Synthetic Seismic, and Flow Simulation

Outcrop modeling studies provide valuable insight into subsurface prediction and reservoir management by revealing the geologic factors that control fluid flow and seismic response. CSS bridges a gap between outcrop and subsurface by providing a growing set of data and quantitative pathways connecting analog to reservoir. 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.

THEME 3: Basin-scale Controls, and Regional Slope Stratigraphy

Knowledge of boundary conditions such as basin history, tectonics, climate, and sediment-routing system configuration provides important context for exploration-scale models and play concepts. The world-class outcrop belts we study provide contextual information for field-scale architecture, reservoir modeling, and seismic characterization research, allowing for more robust comparison within a slope depositional system (longitudinally and/or along-strike), between separate stratigraphic units in the same basin, or among different slope systems.

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:

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Project History: The stratigraphy of deep-water outcrops in the Magallanes Basin, southern Chile has been studied for >60 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 in the 2000s. Starting in 2007, Steve Hubbard led an industrial consortium focused on slope channel deposits of the Tres Pasos Formation. 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 1 of CSS was underway with 13 industry sponsors. **This proposal outlines the rationale and plans for a third three-year phase to begin in July 2019**. Driven by outstanding questions, CSS Phase 3 will see an expansion into other stratigraphic units in the Magallanes Basin, as well as select outcrops in other parts of the world. A new, readily accessible area of investigation will be the Nanaimo forearc basin of Western Canada, which has recently been demonstrated to contain vast outcrops of Cretaceous-aged sediment-routing systems. The world-class outcrop belt will be an ideal area to answer important scientific and modeling questions, and is ideally situated for field-based training.

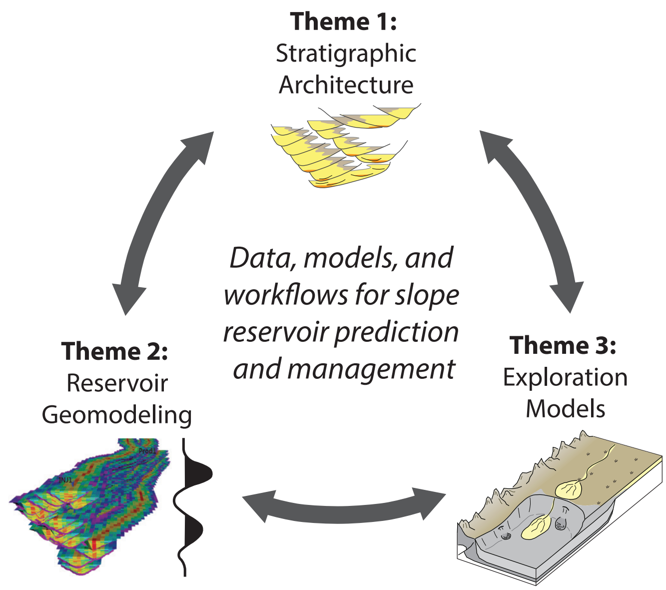

Figure 1. CSS research themes and applications emphasize an integrated approach.

Project Background: 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 quantifying and reducing uncertainty in subsurface prediction/characterization and reservoir model construction. For CSS Phase 3, two sedimentary basins will be specifically emphasized.

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 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 shift in external drivers on sedimentation; and high-relief slope systems on the order of >1 km high (paleobathymetric relief) and at least 40-50 km long (from paleo shelf edge to lower slope) of the Tres Pasos Formation. These high-relief slope systems have been the principal focus of CSS Phases 1 and 2, including the deposits of stacked channel complexes up to 300 m thick that have been used as analogs to reservoirs around the globe (Fig. 2B, C). The basin also contains widespread basin plain mudstones and mass-transport deposits, as well as ponded slope fan strata. These additional depositional settings will be a focus of Phase 3 research (Fig. 2D). The mapping and chronostratigraphic work from Phases 1 and 2 (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 (Fig. 3A-B). Initial work has shown the prevalence of seismic-scale slope channel systems, as well as the deposits of channel-lobe transition zones and submarine fan lobes (Fig. 3). 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. A recently established chronostratigraphic framework for the basin provides the foundation for planned CSS research (Fig. 3B).

Outcrop information from the Magallanes Basin has formed the foundation of a **digital database** that we have used to: (1) refine conceptual models of stratigraphic architecture along deep-water slopes at regional to reservoir scales (Fig. 4); (2) develop statistical relationships between facies and architectural element stacking patterns (Fig. 2B); (3) investigate the impact of multi-scale deep-water architecture on seismic-reflectivity responses (Fig. 4); and (4) examine reservoir connectivity, flow performance, and reservoir model building with the high-resolution 3-D architectural data and knowledge derived from the outcrop database (Fig. 4). Building on our established methods, we will continue to investigate new areas in the Magallanes Basin, and beyond. We will emphasize previously understudied reservoir analogs (e.g., unconfined to confined lobes, basin plain mudstones) and development of workflows (e.g., modeling at complex scales).

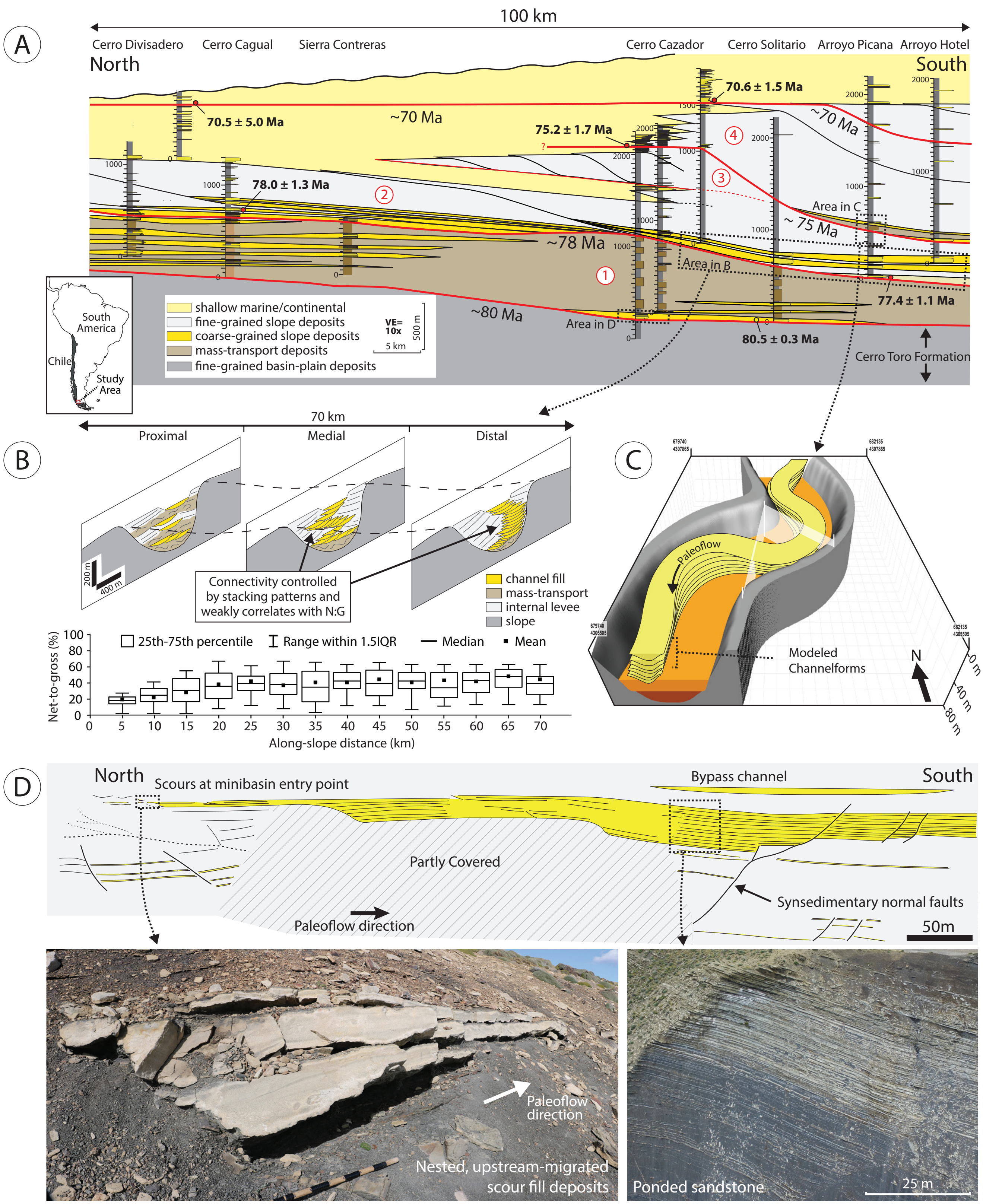

Figure 2. (A) Seismic-scale depositional dip-oriented cross-section of Upper Cretaceous Tres Pasos Formation slope systems, Magallanes Basin, southern Chile. Composite stratigraphic sections constrain four phases of basin evolution (numbered red circles): 1) widespread mass-wasting with intercalated ponded slope fans; 2) establishment of high-relief (>1000 m) slope clinoform system; 3) major transgression and progradation of moderate-relief (300-400 m) slope clinoform system; 4) Re-establishment of high-relief slope system. The initiation of Phases 2 (Part B) and 3 (Part C) were associated with development of slope channel systems that extended >30-50 km into the basin; composite sedimentary packages are comparable in dimensions and internal character to numerous reservoirs globally. The initiation of Phase 1 (Part D) resulted in the establishment of a series of growth-fault bound minibasins, with thick-bedded sandstone onlapping up-dip slope. The up-dip sandstone pinch-out is characterized by a series of discontinuous scour fills that formed as flows expanded into the depocenter.

Additional Information: www.chileslopesystems.com

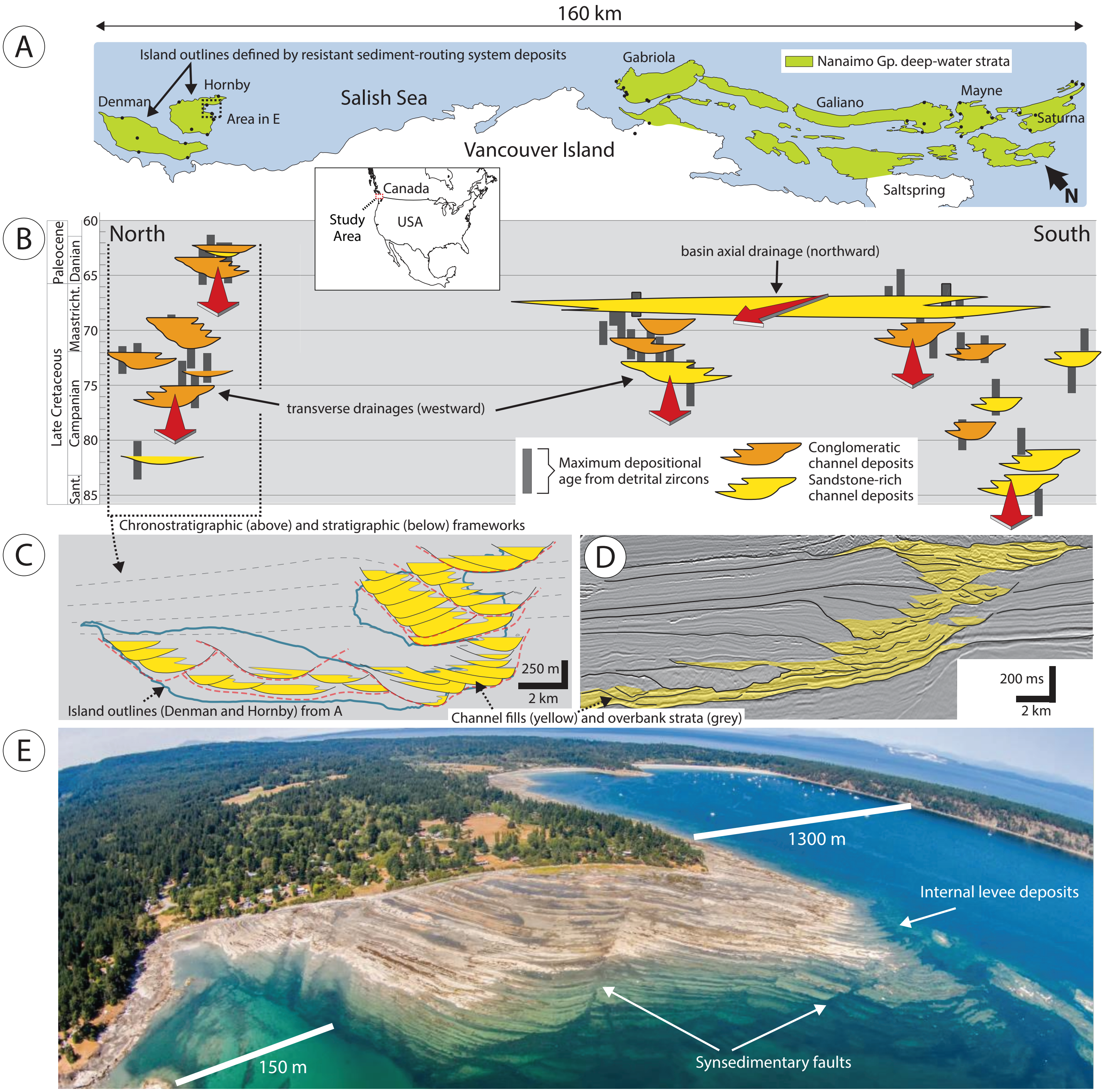

Figure 3. (A) Study area and (B) chronostratigraphic framework of the Upper Cretaceous deep-water Nanaimo Basin (inset map shows location in the Pacific Northwest). The outcrop transect features a largely strike-oriented cross-section 160 km long and almost 2 km thick. Regional mapping and geochronology constrains the position and timing of a series of sediment-routing systems along the basin margin. (C) The stratigraphic architecture of the two northernmost islands, Hornby and Denman, features evidence for an early phase of lateral channel migration followed by a late phase of vertically aligned aggradational channels. (D) The scale and evolutionary pattern is comparable to prospective channel systems, including offshore Tanzania (Part D; seismic profile modified from Sansom, 2018; Petroleum Geoscience). (E) Outcrops of the Nanaimo Basin are best exposed in broad intertidal areas, and feature channel, overbank, channel-lobe transition, and lobe strata (outcrop location in Part A).

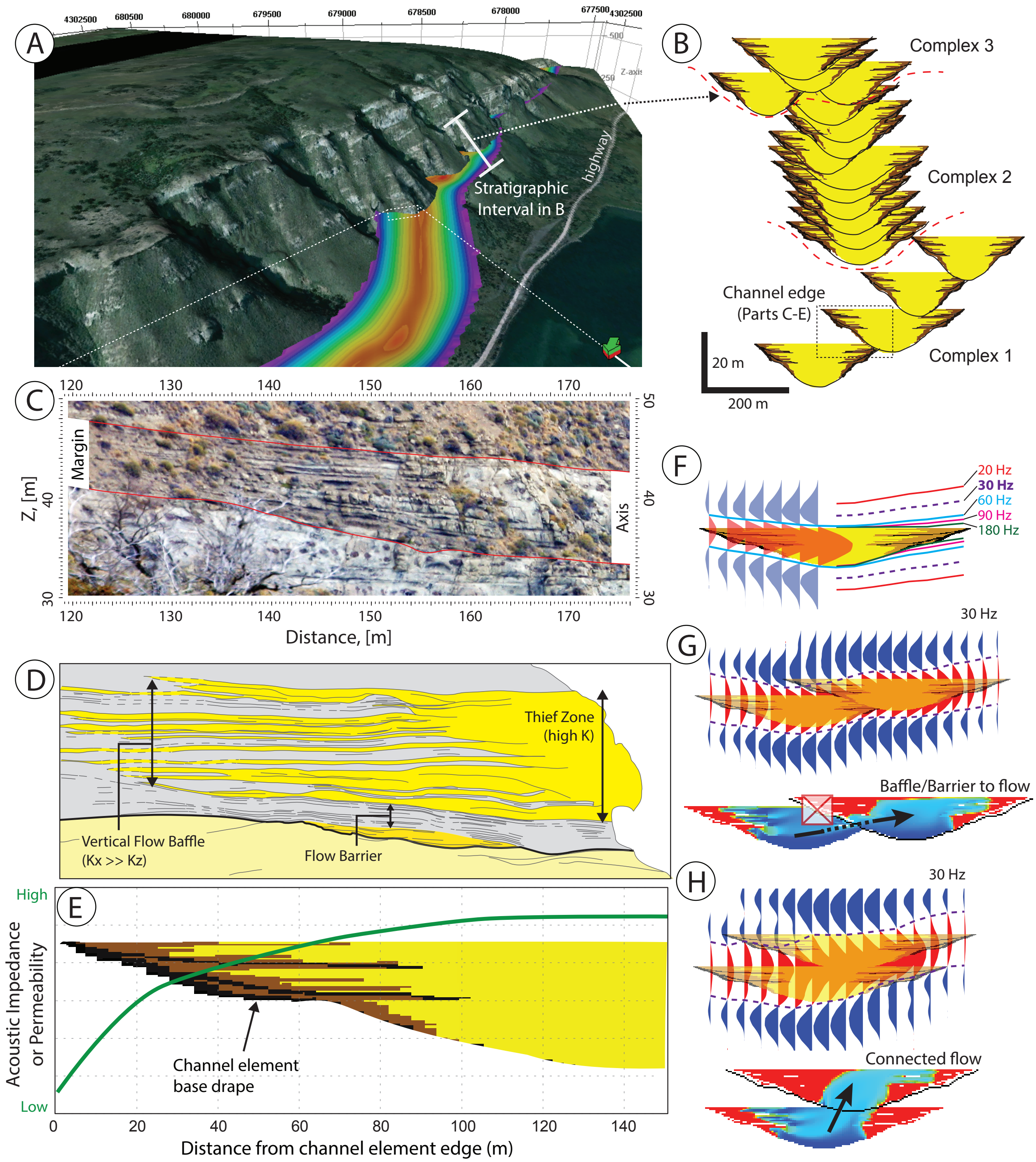

Figure 4. (A) Outcropping strata from the Magallanes Basin (Tres Pasos Formation) highlighting 100-300 m thick channel units. A single modeled channel element, ~300 m wide and 14 m thick, is projected based on outcrop observations. Hot colors represent sand-rich channel-axis facies and cool colors represent sandstone-poor channel-margin facies. (B) Bed-scale heterogeneity and channel element architecture is incorporated into composite, seismic-scale channel complexes using data from detailed measured sections and surveyed stratigraphic surfaces (<10 cm resolution differential GPS). Data is integrated into a 3-D architectural model, from which the cross-section shown was extracted. (C) Photograph, (D) line drawing, and (E) template-model of the channel element axis-to-margin facies transition, highlighting the intra-element stratigraphic architecture. Analog rock properties from subsurface fields are used for forward seismic and flow modeling. Both impedance and permeability are high in channel axis positions and decrease toward channel margins. (F) Apparent thickness interpretations from forward seismic models of a single channel element at different frequencies using shallow offshore West Africa rock properties. (G, H) Two-channel element models reveal fundamental bed- to geobody-scale seismic response and flow behavior. In laterally stacked channel elements (G), channel margin facies baffle or impede flow. Instances where channel elements are aligned and aggradational (H), vertical juxtaposition of axis facies can result in development of a thief zone, and rapid water breakthroughs.

Previous Results and Deliverables: Phase 1 and 2 work has generated a wealth of fundamental outcrop data (e.g., measured sections, stratigraphic correlations, drone-acquired photogrammetry models) captured digitally in a database (e.g., measured section data including grainsize, facies, bed thicknesses, etc.), which also includes high-resolution GPS surveys. These data have been used to construct 3-D architectural models (in Petrel; e.g., Figs. 2C, 4A,B), and synthetic seismic models from bed- to field-scale (Fig. 4F-H). Our analyses have led to numerous scientific and applied outcomes including: (1) refined conceptual models to explain slope channel-fill patterns (e.g., Hubbard et al., 2014); (2) documentation and interpretation of reservoir-scale slope channel stacking patterns (e.g., Pemberton et al., 2016); (3) quantified impact of stacking patterns and internal architecture on connectivity and seismic responses for channelized reservoir strata (e.g., Jackson et al., in press); and (4) development of novel geochronological techniques for enhanced regional-scale correlations in deep-water basins (e.g., Daniels et al., 2018). Phase 2 has supported the research of 3 M.S. students, 5 Ph.D. candidates, 1 post-doctoral fellow, 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). We are continually exploring new ways to interact with sponsors and deliver results.

Phase 3 Research Plan: Our research will be designed and conducted within the framework of our three thematic areas (Fig. 1). A series of focused project activities and their anticipated timelines are proposed in the context of these research themes, as outlined in Table 1. Details of these various project activities are provided in an extended appendix that accompanies this proposal. Notably, we will emphasize a breadth of slope environments in Phase 3 of the research program (Fig. 5). In all instances, studies will be accomplished through the collective effort of students and principal investigators, and in some instances, external collaborators. Data and geomodels grounded in outcrop characteristics are important deliverables from this JIP.

Table 1. Proposed CSS Phase 3 project list and timeline.

Projects	Timeline 2019	2020	2021	2022
THEME 1: QUANTITATIVE, CONCEPTUAL AND ARCHITECTURAL MODELS OF SLOPE STRATIGRAPHY				
1.1 Generalized conceptual models of slope sub-environment architectures using statistical analyses and metrics	← ongoing →			
1.2 Upper slope canyon-channel fills and the prediction of up-dip stratigraphic traps	■	■		
1.3 How do submarine channels fill longitudinally with sand?		■	■	
1.4 Upstream-migrating bedforms associated with supercritical flows in channel-lobe transition zones	■	■		
1.5 High-energy thin-bedded deposits: spatial distribution, reservoir implications, and origin			■	■
1.6 Relationship of internal levee deposits to channel-fill architecture and stacking	■	■		
1.7 Characterization of intra-slope fan sedimentology, stratigraphy, and trap potential	■	■	■	
1.8 Architectural element characterization in mudstone-dominated successions		■	■	■
THEME 2: GEOMODELING, SYNTHETIC SEISMIC AND FLOW SIMULATION				
2.1 Development of an outcrop-derived library of architectural model templates	← ongoing →			
2.2 Near-wellbore modeling of slope channel elements		■	■	
2.3 Surface-based modeling of 3-D architectural elements controlled by near wellbore modeling		■	■	■
2.4 Developing workflows for modeling seismic-scale channel complexes	■	■	■	
2.5 Modeling the impact of channel-related thin-bedded facies on flow and connectivity		■	■	■
2.6 Quantitative seismic response of stratigraphic architecture	■	■		
2.7 Recognizing heterogeneity in inverted seismic data: Implications for reservoir delineation and modeling			■	■
2.8 Coupling seismic inversion with template-based modeling				■
2.9 Hypothesis-based modeling workflows: Application to ponded slope systems		■	■	
THEME 3: BASIN-SCALE CONTROLS AND REGIONAL SLOPE STRATIGRAPHY				
3.1 Influence of syn-depositional deformation on intra-slope fan distribution and architecture	■	■		
3.2 Linking shelf-edge process regime and stratigraphic evolution to deep-water delivery of sand		■	■	
3.3 Tectonic controls on deep-water slope system transitions	■	■		
3.4 Constraining along-strike variability of sediment feeder systems in slope systems	■	■	■	
3.5 Influence of climatic regime on sediment delivery to deep-water slope systems			■	■
3.6 Chronology and rates of sedimentary processes	← ongoing →			

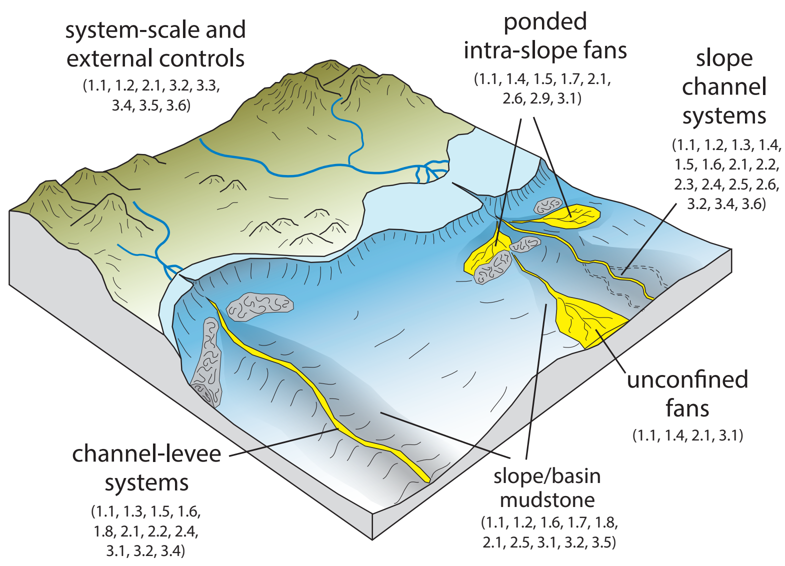

Figure 5. CSS Phase 3 research projects in context of source-to-sink systems. CSS will target the deposits of a series of deep-water subenvironments in order to provide insight into a breadth of ongoing and emerging deep-water reservoirs. See Table 1 for project titles, and the proposal appendix for expanded information about each project.

Deliverables and Sponsor Benefits:

• Access to data, models and scripts: 3-D architectural models (Petrel projects), measured section data (Illustrator/PDF files, correlation panels, Matlab database files), statistical compilations of data (Excel) and Matlab/Python scripts, 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 areas. In 2018, we provided two trips, one to Chile and another to British Columbia. We will consult with sponsors to identify preferred fieldtrip strategies.
  - 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, facilitated through PI visits to offices.

• Opportunities to interact with PIs and students at additional, company-specific site meetings.

• Companies will be acknowledged on all disseminated material.

Key CSS References (2013-2018):

Jackson, A., Stright, L., Hubbard, S., Romans, B.W., accepted, Static reservoir connectivity of stacked deep-water channel fills: AAPG Bulletin.

Pemberton, E.A.L., Stright, L., Fletcher, S., Hubbard, S.M., 2018, Seismic reflectivity modeling of outcropping sandstone-prone deep-water sedimentary bodies: The influence of stratigraphic architecture on seismic response: Interpretation, 6, T783-T808.

Daniels, B.D., Auchter, N., Hubbard, S.M., Romans, B.W., Matthews, W., Stright, L., 2018, The timing of deep-water slope evolution constrained by large-n detrital and volcanic ash zircon geochronology, Magallanes Basin, Chile: GSA Bulletin, v. 130, 438-454.

Pemberton, E.A.L., Hubbard, S.M., Fildani, A., Romans, B.W., Stright, L., 2016, The stratigraphic expression of decreasing confinement along a deep-water sediment routing system: outcrop example from southern Chile: Geosphere, 12, 114-134.

Reimchen, A.P., Hubbard, S.,M., Stright, L., Romans, B.W., 2016, Using sea-floor morphometrics to constrain stratigraphic models of sinuous submarine channel systems: Marine and Petroleum Geology, 77, 92-115.

Auchter, N.C., Romans, B.W., Hubbard, S.M., 2016, Influence of deposit architecture on occurrence and style of intrastratal deformation, slope deposits of the Tres Pasos Formation, Chile: Sedimentary Geology, 341, 13-26.

Covault, J.A., Sylvester, Z., Hubbard, S.M., Jobe, Z.R., Sech, R., 2016, The stratigraphic record of submarine channel evolution: The Sedimentary Record, 14, 4-11.

Stevenson, C.J., Jackson, C.A-L., Hodgson, D.M., Hubbard, S.M., Eggenuisen, J.T., 2015, Deep-Water Sediment Bypass: Journal of Sedimentary Research, v. 85, p. 1058-1081. (40)

Hubbard, S.M., Covault, J.A., Fildani, A., Romans, B.W., 2014, Sediment transfer and deposition in slope channels: Deciphering the record of enigmatic deep-sea processes from outcrop: Geological Society of America Bulletin, 126, 857-871.

Fildani, A., Hubbard, S.M., Covault, J.A., Maier, K.L., Romans, B.W., Traer, M., Rowland, J.C., 2013, Erosion at inception of deep-sea channels: Marine and Petroleum Geology, 41, 48-61.

Macauley, R.V., Hubbard, S.M., 2013, Slope channel sedimentary processes and stratigraphic stacking, Cretaceous Tres Pasos Formation slope system, Chilean Patagonia: Marine and Petroleum Geology, 41, 146-162.

Joint Industry Project

Consortium Terms

Architectural Analysis and Modeling of Slope 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 (2019-2022), 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, models and scripts: 3-D architectural models (Petrel projects), measured section data (Illustrator/PDF files, correlation panels, Matlab database files), statistical compilations of data (Excel) and Matlab/Python scripts, posters, presentations, and reports/papers through a password-protected website.
  - 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