Jurassic–Cretaceous Stratigraphic Evolution of the Magallanes–Austral Deep-Water Foreland Basin, Argentine Patagonia

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Photo by T. Schwartz

Field Trip Guidebook: March 1–6, 2015

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2015 SPODDS Affiliates Trip to Argentine Patagonia

ITINERARY

Refer to maps for location information (Figures i.2 and i.3).

DAY 0: Sunday, 1 March 2015

- All participants arrive in El Chaltén, Argentina
- 5:00 p.m. Presentation and ice-breaker at Estancia La Quinta

Night at Estancia La Quinta, El Chaltén

DAY 1: Monday, 2 March 2015

- All-day hike in Parque Nacional Los Glaciares: basement unconformity, predecessor basin-fill, influence of tectonic inheritance on basin evolution

Night at Estancia La Quinta, El Chaltén

DAY 2: Tuesday, 3 March 2015

- Drive to El Calafate, Argentina: road stops to see/discuss shallow-marine deposits, Paleocene unconformity
- Drive to Magallanes Peninsula: deep-water lobe deposits of the Punta Barrosa Formation
- [Optional] Perito Moreno Glacier (Parque Nacional Los Glaciares)

Night at Hotel Mirador del Lago, El Calafate

DAY 3: Wednesday, 4 March 2015

- Boat trip to Estancia Cristina: hike to see volcaniclastic and shaly fill of the predecessor Rocas Verdes back-arc basin (El Quemado & Rio Mayer Formations)

Night at Hotel Mirador del Lago, El Calafate

DAY 4: Thursday, 5 March 2015

- Boat trip down the Brazo Sur (Lago Argentino): hike to see deep-water lobe deposits of the Punta Barrosa Formation, including turbidite and transitional flow deposits

Night at Hotel Mirador del Lago, El Calafate

DAY 5: Friday, 6 March 2015

- Boat trip down the Brazo Sur (Lago Argentino): hike to see coarse-grained canyon-fill (?) deposits of the Cerro Toro Formation; basin-scale implications for facies distribution

Night at Hotel Mirador del Lago, El Calafate

Saturday, 7 March 2015

- All depart El Calafate

2015 SPODDS Affiliates Trip to Argentine Patagonia

PARTICIPANT LIST

SPODDS

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Current SPODDS Affiliates List

Aera Energy, Anadarko Petroleum Corporation, Aramco Services Co., Chevron, ConocoPhillips, Eni S.p.A., Hess Corporation, Karoon Gas Australia Ltd., Nexen, Occidental Petroleum (Oxy), PTT Exploration and Production (PTTEP), Reliance Ltd., Rohöl-Aufsuchungs AG (RAG), Schlumberger, Shell, and Statoil, Yacimientos Petroliferos Fiscales (YPF)

2015 SPODDS Affiliates Trip to Argentine Patagonia

FIELD SAFETY GUIDE

Welcome to 2015 SPODDS Affiliates trip to Argentine Patagonia! Because this trip will take place solely in the field, the next few pages outline the associated health and safety issues and serves to inform you of potential hazards that need to be considered for your participation. It is important for you to evaluate the stated risks with regard to your own personal health and safety, and modify your participation or attendance accordingly.

EMERGENCY PHONE NUMBERS

- **Police:** +(54) 101
- **Ambulance:** +(54) 107
- **Fire:** +(54) 100
- **Hospital:** +(54) 491001
    - Address: Hospital Municipal; Av. Roca 1478, El Calafate, Santa Cruz, Argentina
- **Stanford Satellite Phone:**
    - Phone kept off to retain battery, unless arranged otherwise.
- **Stanford School of Earth Sciences Safety Liaison:**
    - Tom Koos – (650) 465-5774 – cell phone
- **On-Call International:** (603) 328-1956
    - Worldwide medical information/assistance

Overview: Each person is primarily responsible for his/her own safe conduct, as well as contributing to the welfare of the entire group. If you are not comfortable participating in any of the particular activities for any reason, you are encouraged to notify the field trip leader(s). There are no negative implications for this decision. If you become uncomfortable with the actions or behavior of your fellow participants or of the leaders, notify the leader(s).

Driving: Driving, as always, is a big safety concern. We will be driving primarily on paved roads and hard dirt roads that are in variable condition.

- SEAT BELTS – wear your seat belt at all times.
- DISTANCE, DUST – keep a safe distance between cars; avoid dust clouds
- TIRES, OIL, GAS – check your tires and fluids daily

Environmental Hazards/Conditions

1. **Weather:** Weather is notoriously fickle in Patagonia. Be prepared for daytime temperatures ranging from 80°F (27°C) to 32°F (0°C). Be prepared for all types of precipitation, as rain and snow are common. On sunny days, wear sunscreen to prevent blistering. Also, Patagonia is characteristically VERY WINDY. *We suggest having rain- and wind-breaking layers with you at all times.*
2. **Hiking:** The hiking on this trip will be intense. The terrain is steep, and much of the hiking is <u>not</u> on trails. This means that you will be walking over all types of surfaces

(rock, scree, mud, vegetation, etc.). Elevation gains will be up to ~1,000 m and hiking distances will be up to ~10 km.

   a. If at any moment you feel that the hike is too strenuous, **STOP** and let one of the leaders know. **Drink plenty of water** to avoid dehydration, even if it is cold weather.
   b. Wear appropriate hiking boots and watch your step. There are loose and/or in-place rocks that present trip and fall hazards. Rain, snow, and hail contribute to wet surfaces that can be slippery. *We insist that you wear sturdy, durable hiking boots on all hikes. Gaiters are optional.*
   c. **Falling rocks:** As with any outcrop, cliff exposures have the danger of falling rocks – stay away from cliffs! Be aware of where people are below and above you. Do not kick/throw rocks.

3. **Wildlife:** The only dangerous animal is the mountain lion (puma). They are generally reclusive. If you encounter one, make noise to scare it away. DO NOT turn around and run away – this mimics its prey.
4. **Flora:** Most of the vegetation you encounter will be prickly, but is more annoying than hazardous. Do not eat any berries that you see growing on bushes, as some of them are poisonous. *We commonly wear gaiters over our boots/pants to combat the bushes.*
5. **NO SMOKING: <u>Absolutely no smoking.</u>** Strong, dry winds in the area have potential for spreading wildfire quickly. Such an instance burned about half of P.N. Torres Del Paine in 2011, resulting in a large international political debacle. So, we'll say it again: NO SMOKING.

Personal Health

- **Medications:** Persons taking medication(s) are advised to alert the leader(s) of any special medications they may be taking before any emergency situation arises.
- **Allergies:** Persons with known allergies to insect bites, foods, etc. should make such allergies known to the leader(s) so that the appropriate actions can be taken in the event of an emergency.
- **Prevention:** Sun block, insect repellent, and proper clothing will be needed to reduce the chance of sunburn, insect bites, and overexposure.

Boat Hazards (Days 3, 4, & 5)

- The boat ride to Ea. Cristina (Day 3) will be on a large tourist boat that allows viewing from the decks. If the weather and/or waves are bad, the crew will mandate all passengers to vacate the decks and stay inside.
- The boat rides at Brazo Sur (Days 4, 5) will be on a small commercial boat that carries 10-12 people. Be aware of your surroundings and instructions from the captain at all times.

Other:

- **Satellite Phone:** The trip leaders will have two (2) satellite phones at all times in case of emergency.
- **Med Kits:** The trip leaders will also have various medical kits to treat minor injuries.

GEOLOGIC BACKGROUND

The Jurassic to Neogene basin evolution of southern Patagonia consists of a two-phase history, including a back-arc rift phase (the predecessor Rocas Verdes basin) and a successor retroarc foreland basin phase (Magallanes-Austral basin) (Wilson, 1991; Fildani & Hessler, 2005; Calderon et al., 2007; Romans et al., 2010). The southern Patagonian Andes region of South America was characterized by a back-arc extensional province during Jurassic-Early Cretaceous time (Figs. i.4, i.5) (Katz, 1963; Dalziel et al., 1974; De Wit & Stern, 1981; Biddle et al., 1986). Lithospheric extension is recorded through bimodal volcanism including basalt and gabbro of the Sarmiento ophiolite complex and widespread silicic volcanism of the El Quemado, Ibañez, and Tobifera Formations (Saunders et al., 1979; Pankhurst et al., 2000; Calderon et al., 2007). The resulting syn-rift Rocas Verdes basin was filled by volcaniclastic units associated with the silicic volcanics mentioned above, and by black shale of the Rio Mayer and Zapata Formations in Argentina and Chile, respectively (Fildani & Hessler, 2005).

The transition from back-arc extension to compression is recorded by flexural deepening of the foredeep from 100-500 m water depth during Aptian-Albian time to up to 1000-2000 m by Albian-Cenomanian time (Natland et al., 1974). The formation of a fully-developed foreland basin is represented by the onset of deep-marine coarse clastic deposition of the Punta Barrosa Formation (Wilson, 1991; Fildani et al., 2003; Fildani & Hessler, 2005). The presence of inherited, attenuated crust related to the early extensional phase allowed for prolonged deep-marine sedimentation during Late Cretaceous time (Fildani & Hessler, 2005; Romans et al., 2010; Romans et al., 2011). Continued evolution of the foreland basin resulted in a deep-marine axial channel belt that delivered sediment from north to south, as recorded by the Cerro Toro Formation (Winn & Dott, 1979; Crane & Lowe, 2008; Hubbard et al., 2008; Jobe et al., 2010). This, in turn, is overlain by the Tres Pasos Formation, which records southward progradation of the continental-scale, deep-marine slope (Schultz et al., 2005; Armitage et al., 2009; Romans et al., 2009; Hubbard et al., 2010). Ultimately, deep-marine facies transition upward into shallow- and marginal-marine deposits of the Campanian-Maastrichtian Dorotea Formation (Covault et al., 2009; Romans et al., 2011; Schwartz & Graham, 2014).

Jurassic rift-related and Cretaceous foreland basin strata are now exposed in vast exposures along the south Andean fold-thrust belt (green areas in Fig. i.2; Fig. i.3). World-class exposures in the Ultima Esperanza District of Chile, directly to the south of the areas we will visit on this trip, beautifully record the prolonged deep-marine history of the Late Cretaceous Magallanes foredeep. Outcrops visited during this trip are intended to evaluate relationships with northern (up-depositional-dip) lithostratigraphic equivalents (e.g., Fig. i.7) and to elucidate the rift-related basin history that preceded Late Cretaceous foreland basin sedimentation.

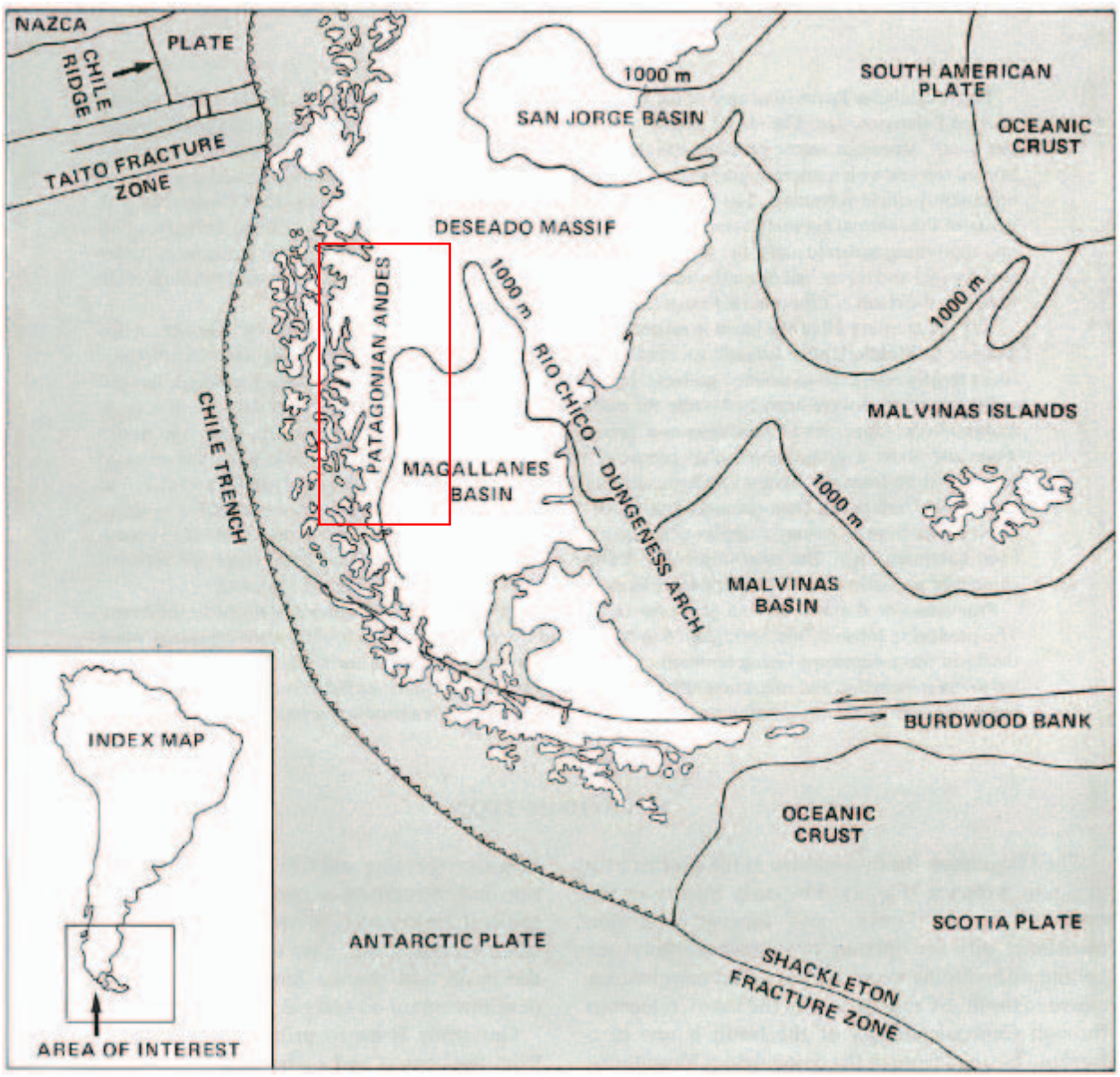


Figure i.1. Present-day tectonic setting of the Magallanes-Austral basin (from Biddle et al., 1986). Red box denotes area of current and previous SPODDS research in the Chilean (Magallanes) and Argentine (Austral) sectors of the basin.

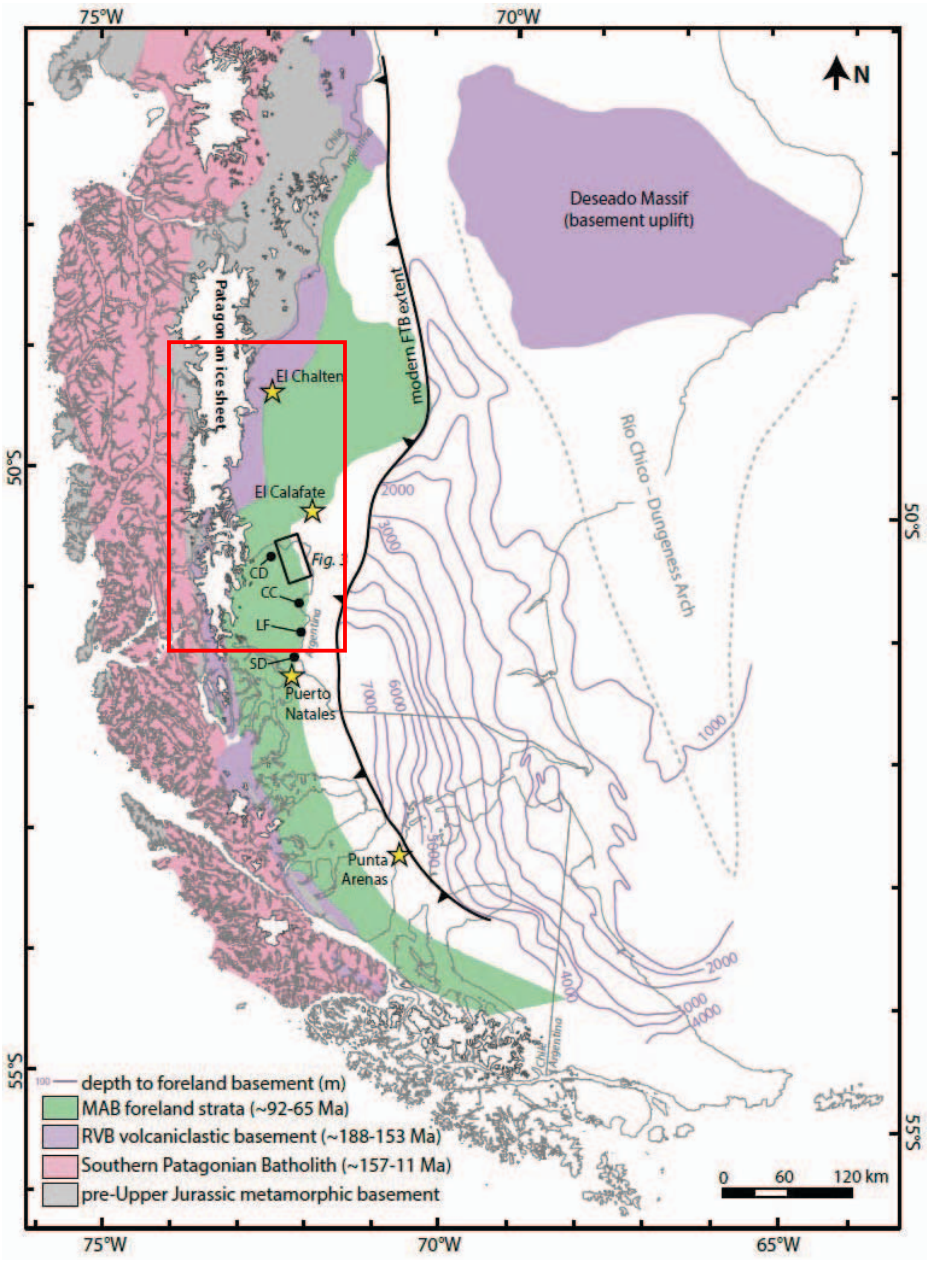
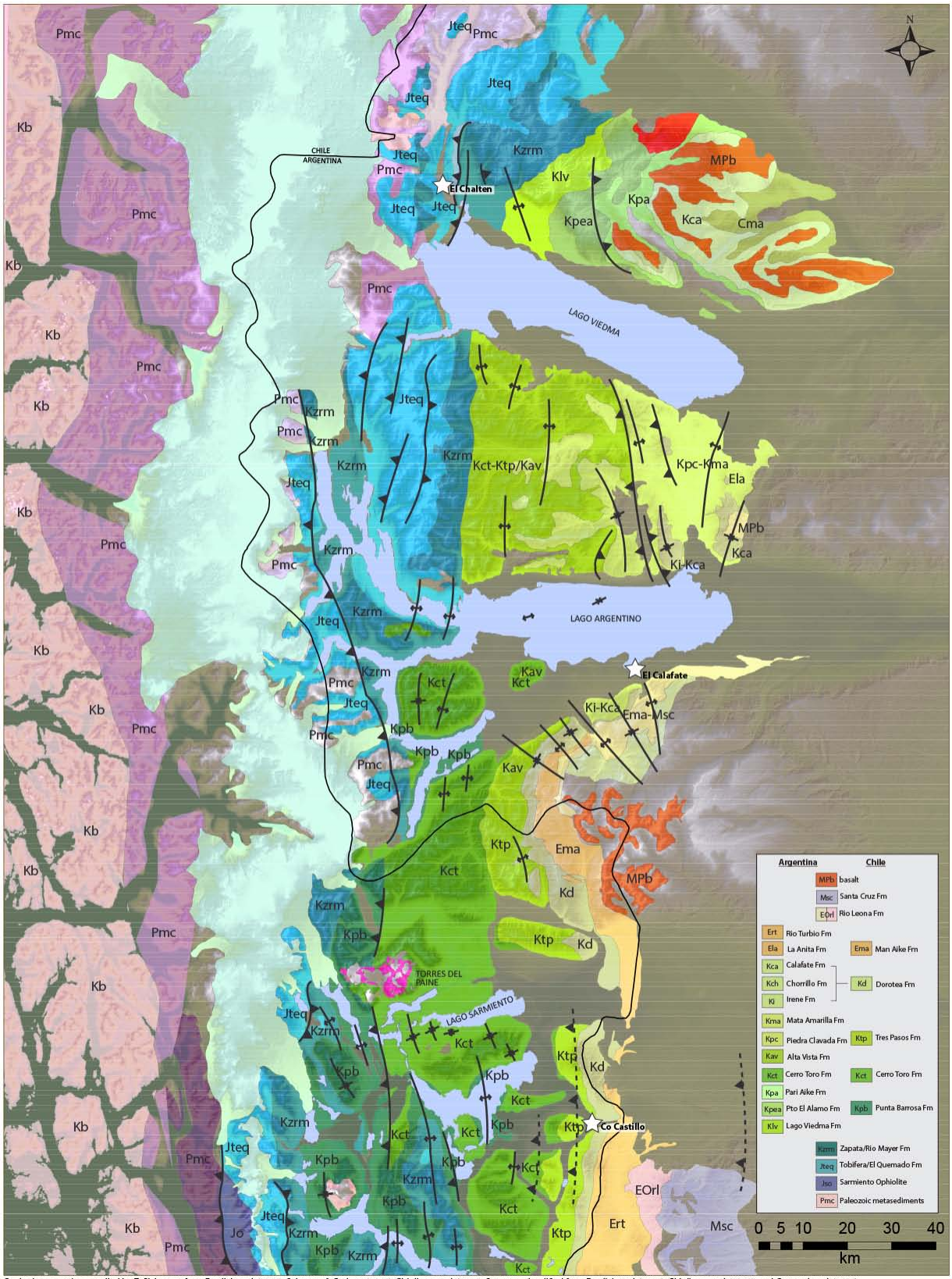


Figure i.2. Simplified tectonostratigraphic map of southern South America (from Schwartz & Graham, 2014). The South Patagonia batholith (pink) is hosted in a complex of Paleozoic metasedimentary rocks (gray). The Patagonian fold-thrust belt consists of bimodal volcanic rocks associated with the predecessor Rocas Verdes basin (purple), deep- to marginal-marine siliciclastic rocks associated with the Late Cretaceous Magallanes-Austral foreland basin (green), and shallow- to non-marine siliciclastic rocks associated with the Cenozoic foreland basin (not pictured). Depth-to-basement contours (after Biddle et al., 1986) reveal a highly asymmetric foreland basin profile with its deepest parts adjacent to the fold-thrust belt. Red box highlights area of geologic map in Figure i.3.



Geologic map units compiled by Z. Sickmann from Fosdick et al. (2011), Schwartz & Graham (2014), Ghiglione et al. (2009). Structure simplified from Fosdick et al. (2011), Ghiglione et al. (2009), and Coutand et al. (1999).

Figure i.3. Regional geologic map illustrating regional trends in structure and stratigraphy.

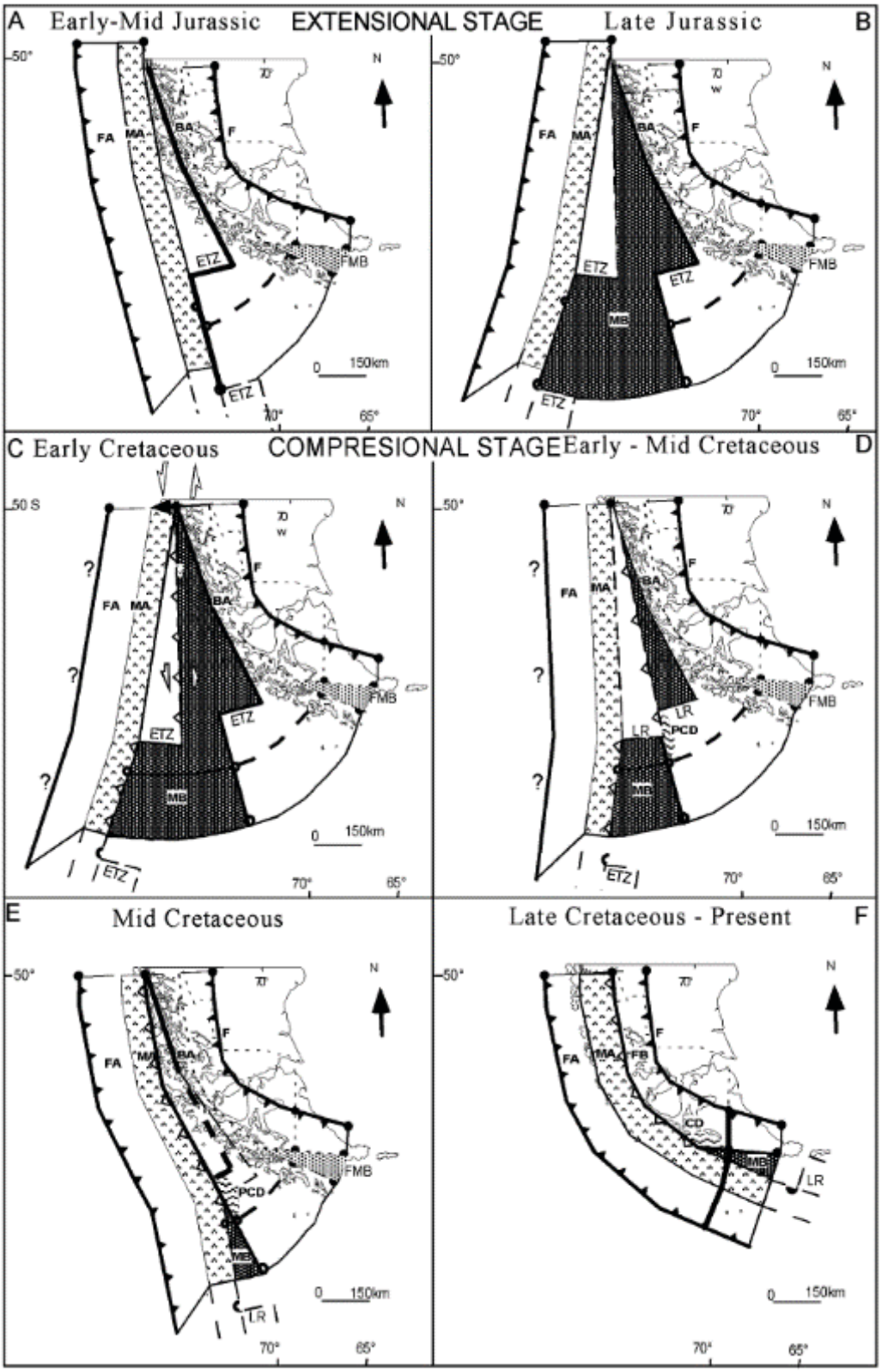


Figure i.4. Time-series of events leading to the generation of the deep-marine Magallanes-Austral retroforeland basin (from Kraemer, 2003).

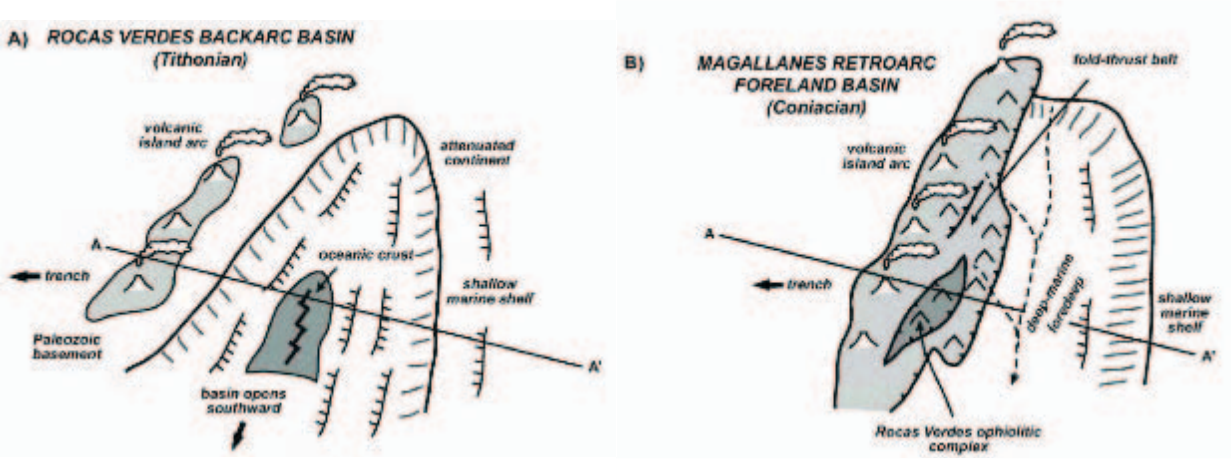


Figure i.5. Schematic diagram illustrating the inherited structure of the predecessor Rocas Verdes marginal basin (from Fosdick et al., 2014). Loading of attenuated crust by the south Andean fold-thrust belt generated an elongate bathyal foredeep during Late Cretaceous time.

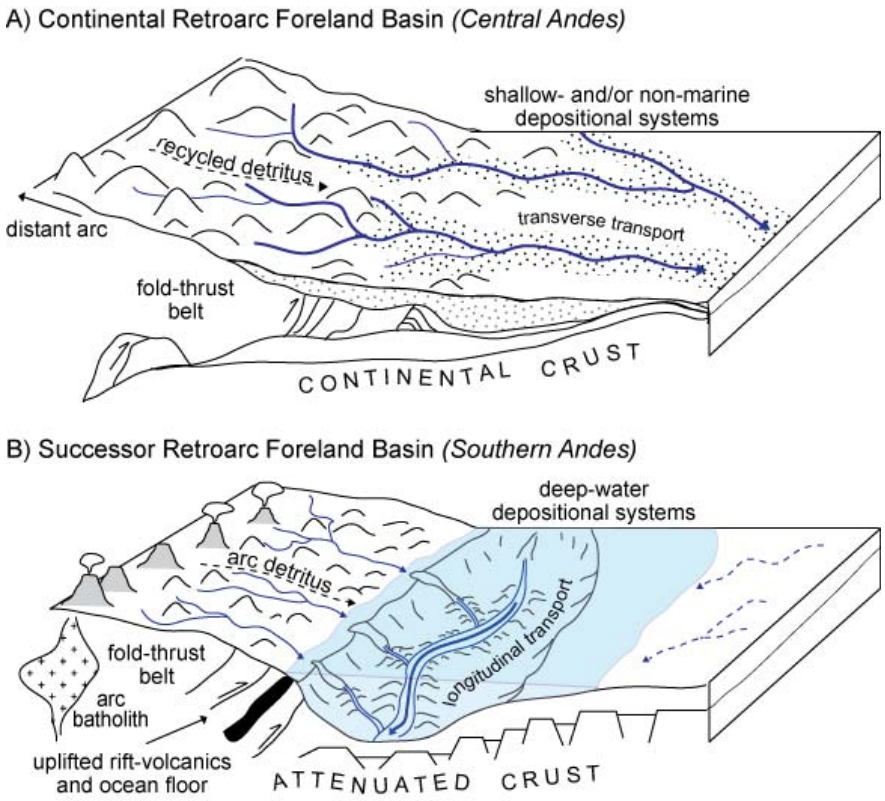


Figure i.6. Schematic cartoons showing the structural and stratigraphic characteristics of two different types of retroarc foreland basin systems (from Malkowski et al., in review): A) continental retroarc foreland basin (after Horton and DeCelles, 1997) such as in the Cenozoic Central Andes, and B) successor retroarc foreland basin (after Romans et al., 2010 and Fosdick et al., 2014), which is more characteristic of the Cretaceous-Paleogene southernmost Andes.

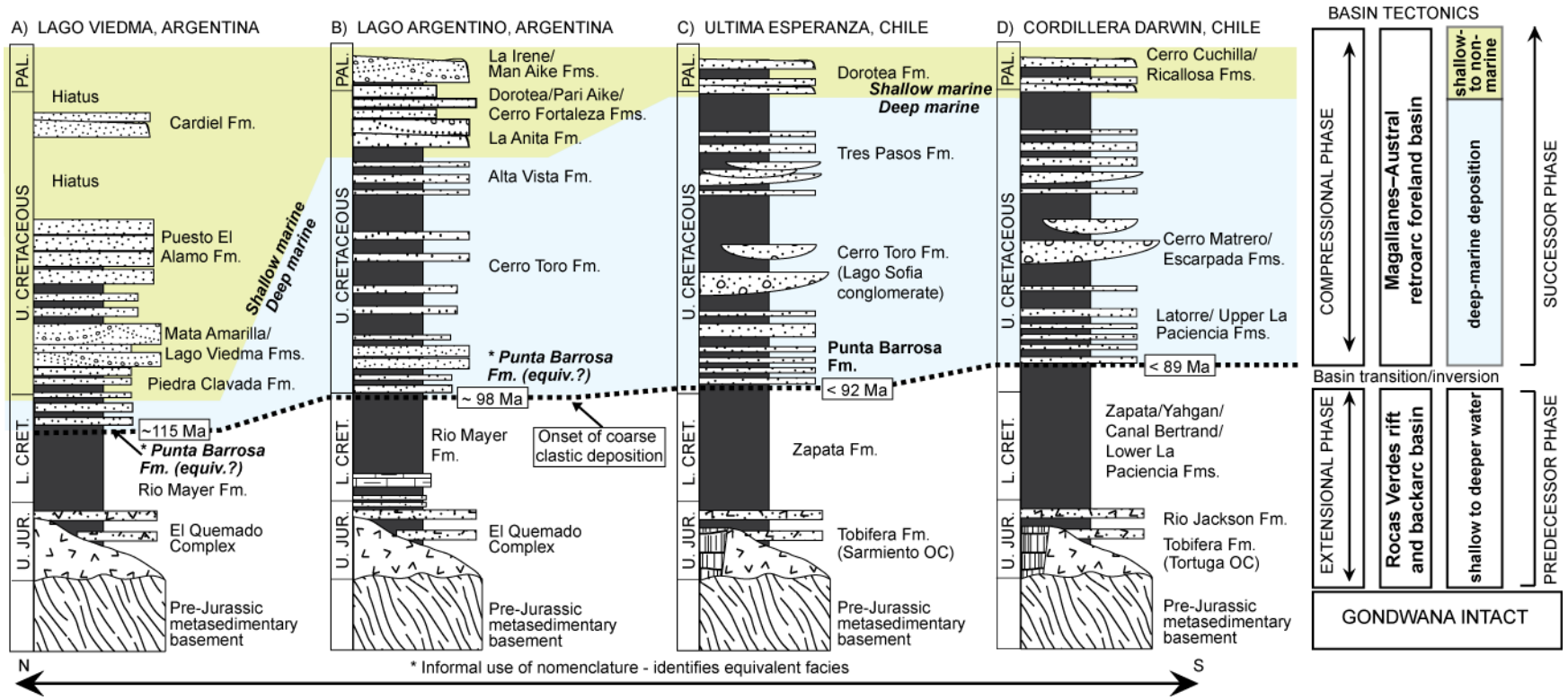


Figure i.7. Generalized stratigraphic correlations between units exposed along-strike (N – S) of the Patagonia fold-and-thrust belt (Malkowski et al., in review). Blue shaded region corresponds to deep-water deposition and green shaded region corresponds to shallow- and non-marine deposition. Generalized stratigraphy of: A) the region just north of Lago Viedma (near El Chalten) in Argentina, modified after Arbe (2002); B) the region just north of Lago Argentinto in Argentina, modified after Kraemer and Riccardi (1997); C) the Ultima Esperanza district of southern Chile, modified after Wilson (1991), Fildani and Hessler (2005), and Romans et al. (2010); and D) the Cordillera Darwin region in Chile, modified after McAtamney et al. (2011).

DAY 0 – Sunday, 1 March 2015

Destination: Estancia La Quinta, El Chaltén, Argentina

All field trip participants should use today to travel from their point of entry (e.g., El Calafate, Argentina or Puerto Natales, Chile) to El Chaltén, Argentina. All participants should meet at 5:00 p.m. for an ice-breaker and introduction to the field trip.

Driving Directions: El Calafate to El Chaltén (approx. 3.5 hours driving time)

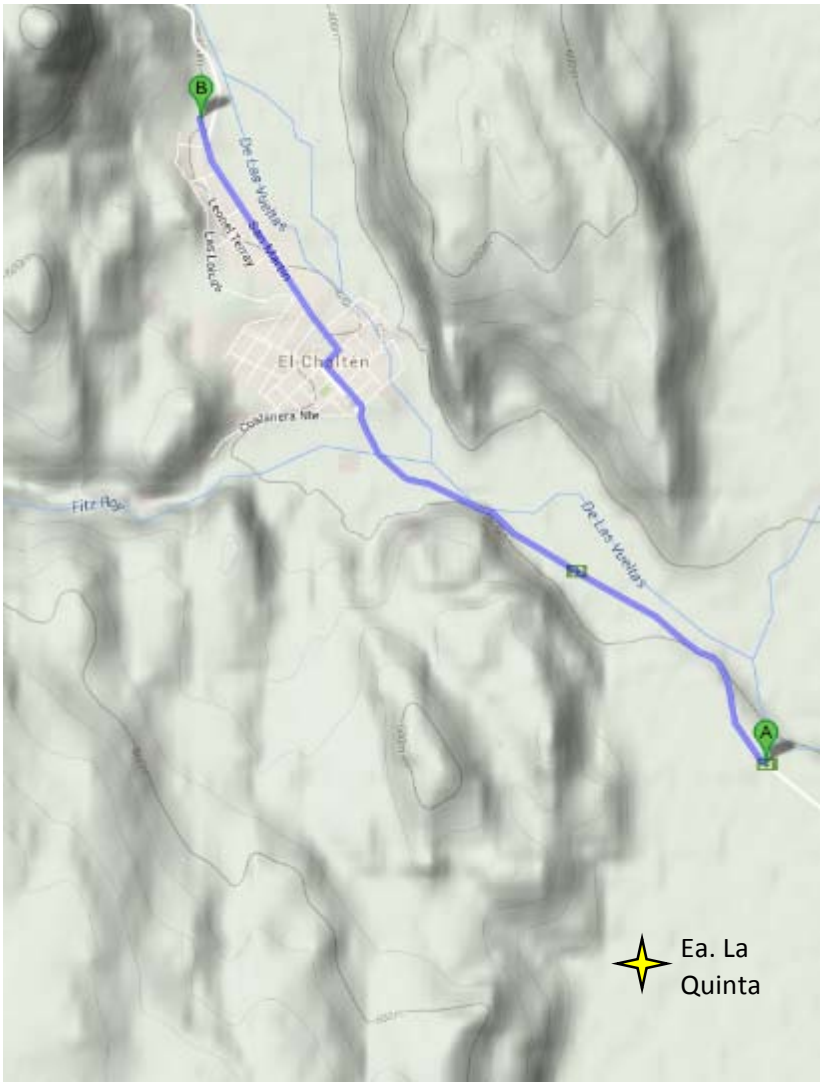
1. From Calafate, drive **east** on **Ruta Provincial 11** (RP11)
    a. From Calafate (city).....28.3 km
    b. From Calafate Airport (FTE).....14.9 km
2. Turn **left** (north) onto **Ruta Nacional 40** (RN40).....94.0 km
3. Turn **left** (west) onto **Ruta Provincial 23** (RP23) toward El Chaltén .....87.6 km
4. At Chalté, turn **left** onto **Costanera Nte** .....0.5 km
5. **Estancia la Quinta** will be on the right.

DAY 1 – Monday, 2 March 2015

Destination: Parque Nacional los Glaciares (El Chaltén)

Today's field trip will consist of an all-day hike in Parque Nacional los Glaciares. Departure time to be determined.

Driving Directions: Estancia La Quinta to Parque Nacional los Glaciares trail head (approx. 10 minutes driving time)



1. Return to **RP23** .....~3 km
2. Turn **left** onto **RP33** toward El Chalten .....2.7 km
3. Slight **left** onto **Miguel Martin de Guemes** ..... 280 m
4. Turn **right** onto **Lago del Desierto** ..... 100 m
5. Take first **left** onto **San Martin** .....1.3 km
6. Continue to end of San Martin. Park at trail head.

The field stops today provide insight into the pre-foreland phase of the Magallanes-Austral basin. We will see the unconformable contact between Paleozoic metamorphic basement rocks and Rocas Verdes rift-basin sediments; will examine the volcaniclastic and shaly fill of the predecessor Rocas Verdes basin; and will discuss the influence of predecessor tectonic structures on Magallanes-Austral basin evolution. As we hike, you will also see beautiful clastic stratigraphy exposed in the high terrain to the east, on Cerro Pyramid and adjacent peaks. This stratigraphy is interpreted to be shallow-water equivalents to deep-marine Punta Barrosa facies we will see on Days 2 and 4.

Post-depositional events including continued Cretaceous – Miocene crustal shortening, intrusion of the Cerro Fitz Roy intrusive complex, and Pleistocene alpine glaciation are responsible for the striking physiographic features of the sub-Andes, and have provided superb exposure of the Rocas Verdes and Magallanes-Austral basin fill.

Accommodations (2 March): Estancia La Quinta, El Chaltén.

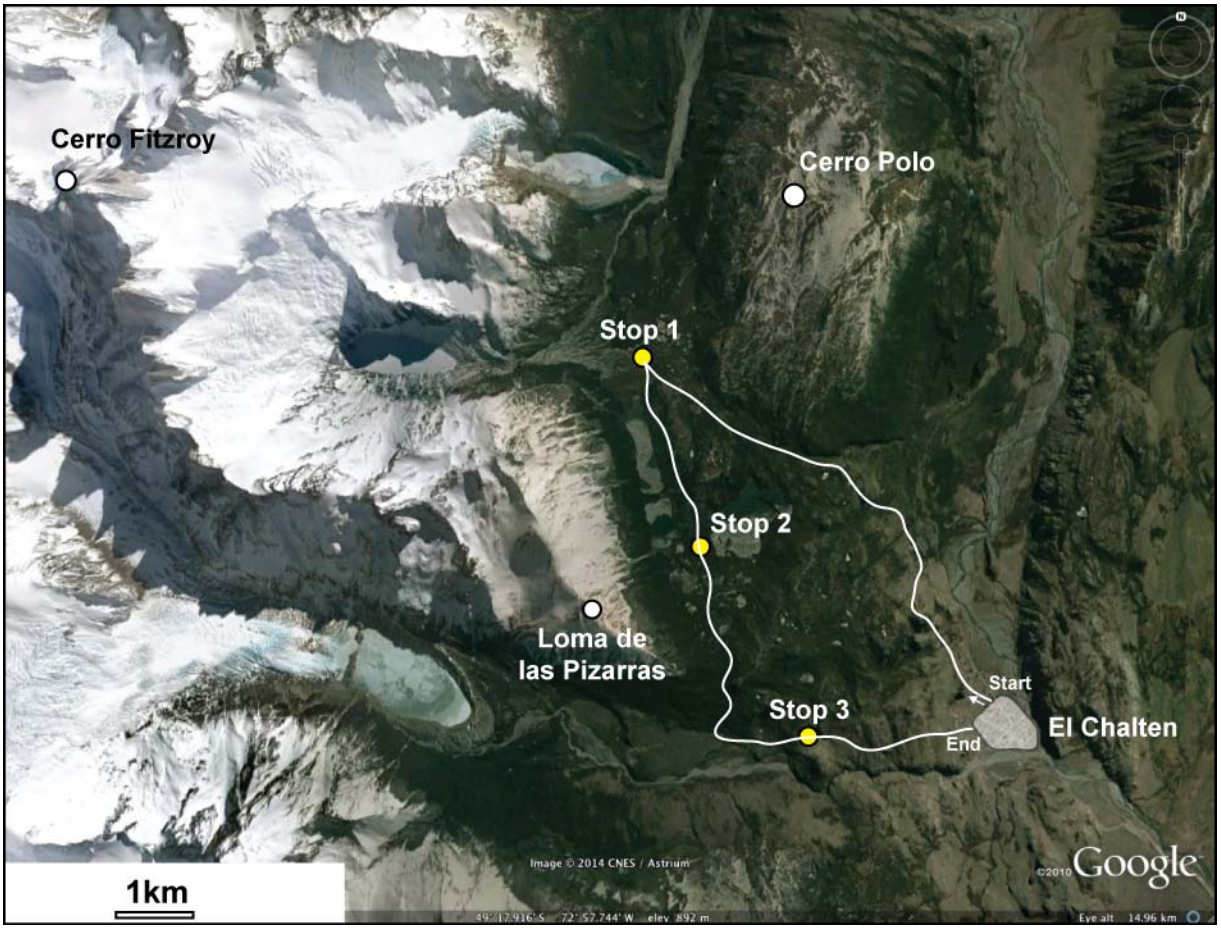


Figure 1.1. Google Earth map showing the general route and stop locations. Stop 1 will include viewing and discussing the basement and predecessor basin history exposed on Cerro Polo, Stop 2 will feature discussion about the onset of coarse clastic deposition during the Cretaceous exposed along the Loma de las Pizarras, and Stop 3 will include viewing and discussing the stratigraphy exposed along Cerro Pyramide toward the east.

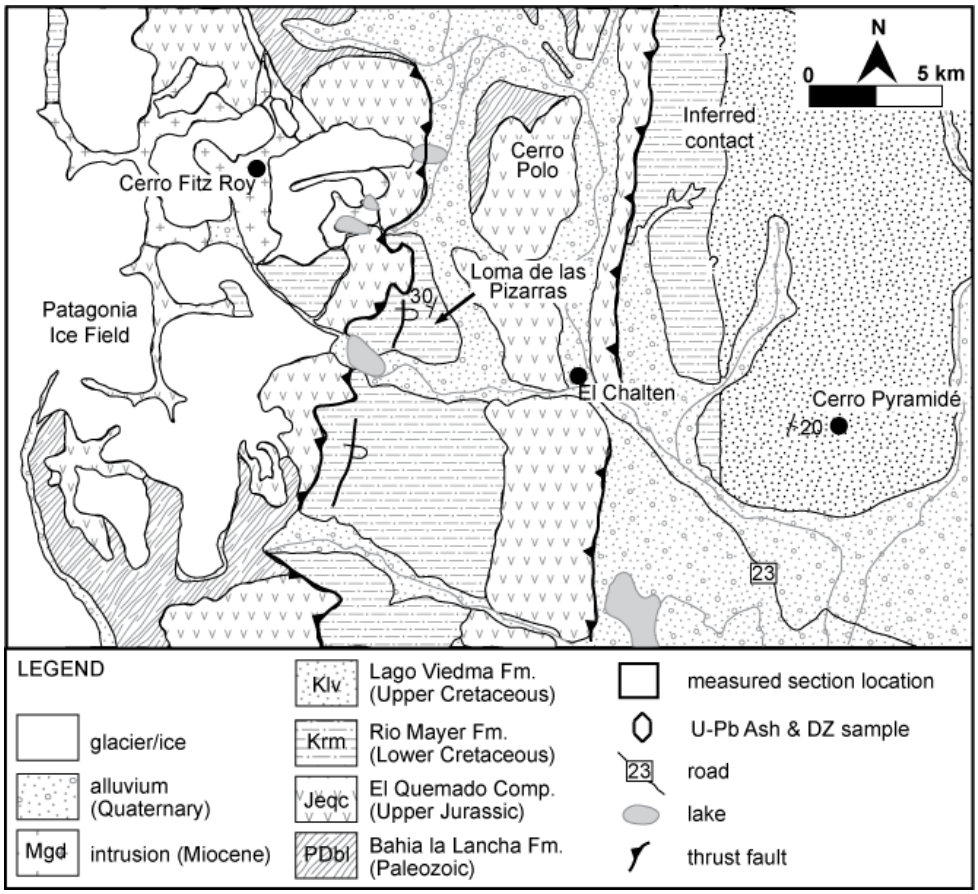


Figure 1.2. Geologic map of the area surrounding El Chalten, Argentina (from Malkowski et al., in review). Modified from Kosmal and Spikermann (2001).

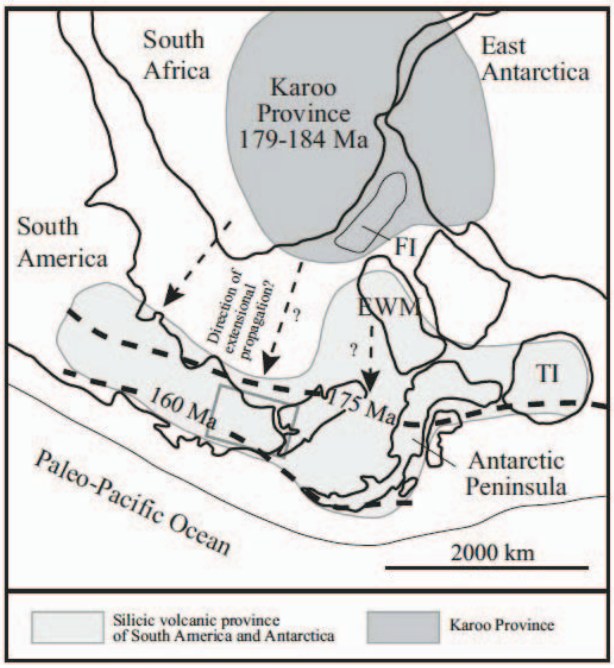


Figure 1.3. From Fildani and Hessler (2005) - Sketch map diagram modified and simplified from Pankhurst et al. (2000), illustrating the silicic volcanic province of Patagonia and the Antarctic Peninsula in relation to the Jurassic magmatism related to the extensional phase of Gondwana breakup. Base map and interpretations obtained from Pankhurst et al. (2000). Contours of 175 Ma and 160 Ma are drawn from Pankhurst et al. (2000), integrated and modified with ages from Féraud et al. (1999), and two ages from Fildani (2004). Blocks sketched: EWM—Elleworth-Whitemore Mountains; FI—Falkland Islands; TI—Thurston Island. Area of interest (Southern South America in box).

STOP 1: Break-up unconformity, Cerro Polo

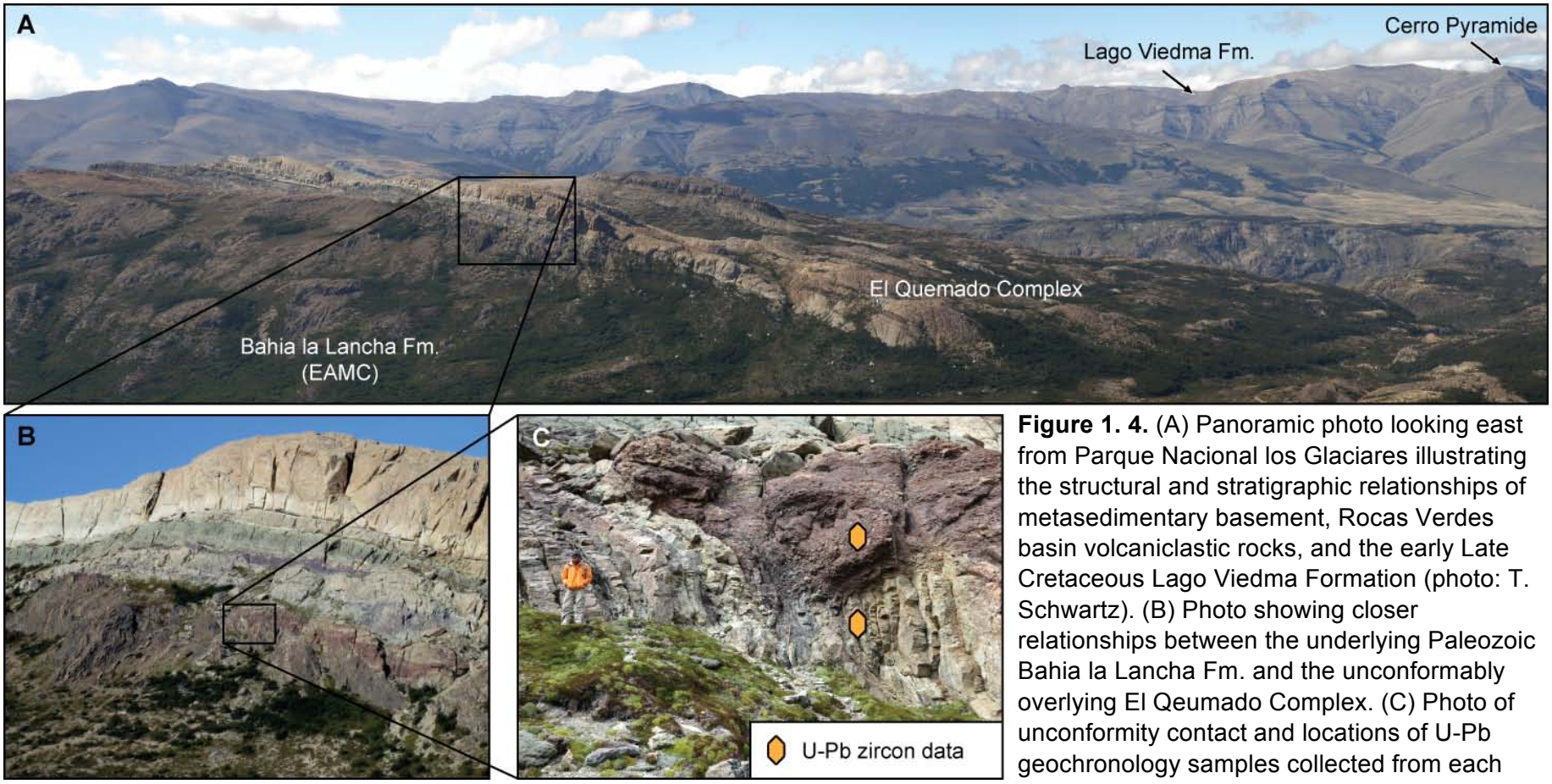


Figure 1. 4. (A) Panoramic photo looking east from Parque Nacional los Glaciares illustrating the structural and stratigraphic relationships of metasedimentary basement, Rocas Verdes basin volcaniclastic rocks, and the early Late Cretaceous Lago Viedma Formation (photo: T. Schwartz). (B) Photo showing closer relationships between the underlying Paleozoic Bahia la Lancha Fm. and the unconformably overlying El Qeumado Complex. (C) Photo of unconformity contact and locations of U-Pb geochronology samples collected from each unit (person for scale).

Notes:

STOP 2: Loma de las Pizarras – early onset of Cretaceous coarse clastic deposition

Figure 1.5. Photopans along Loma de las Pizarras showing the transition from dominantly mudstone to coarser grained sandstone units. (A) A view toward the southwest shows folded and faulted sections of the Rio Mayer Formation. (B) Looking up and north (backside of A) from near the base of the measured section shown in Figure 1.7. Note that these units are as tabular and laterally extensive as far as they are exposed. The vertical white line is approximately 10 meters for scale.

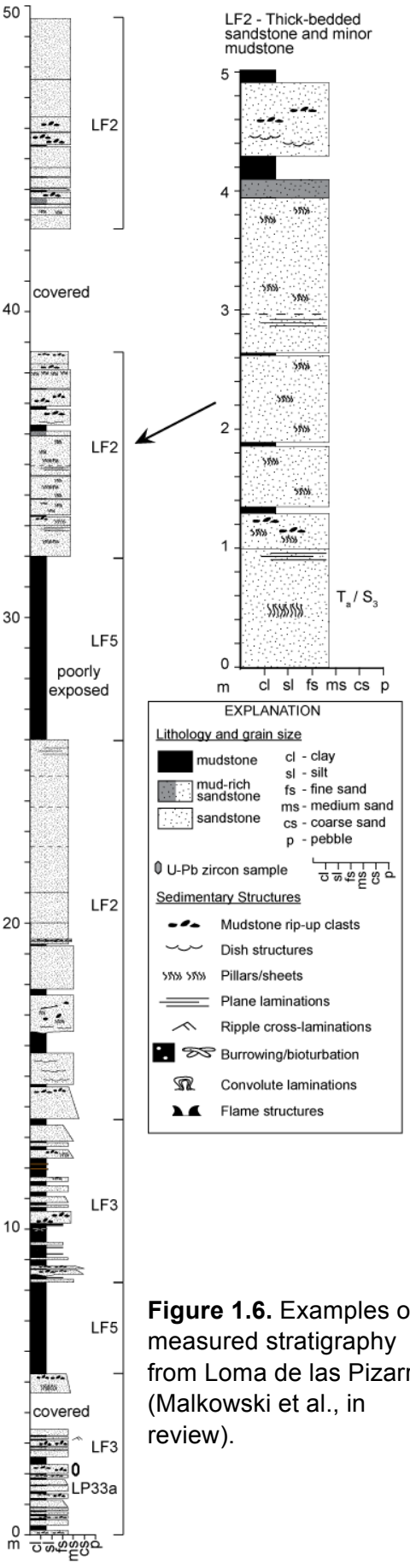


Figure 1.6. Examples of measured stratigraphy from Loma de las Pizarras (Malkowski et al., in review).

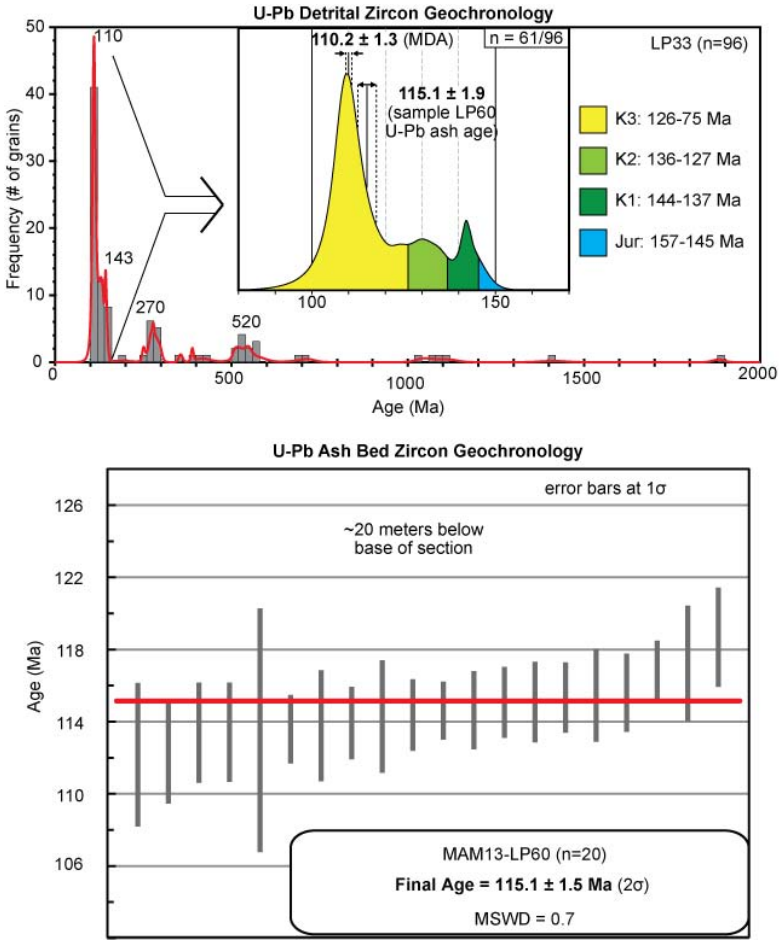


Figure 1.7. U-Pb zircon geochronology from Loma de las Pizarras (from Malkowski et al., in review). Top graph shows detrital zircon age spectra, which reveal a principally arc-derived source. Lower graph shows the ages and uncertainties from an ash horizon sampled ~20 below the base of the stratigraphic section and sample LP33. These data suggest that deep-water coarse clastic deposition may have started much earlier than previously thought.

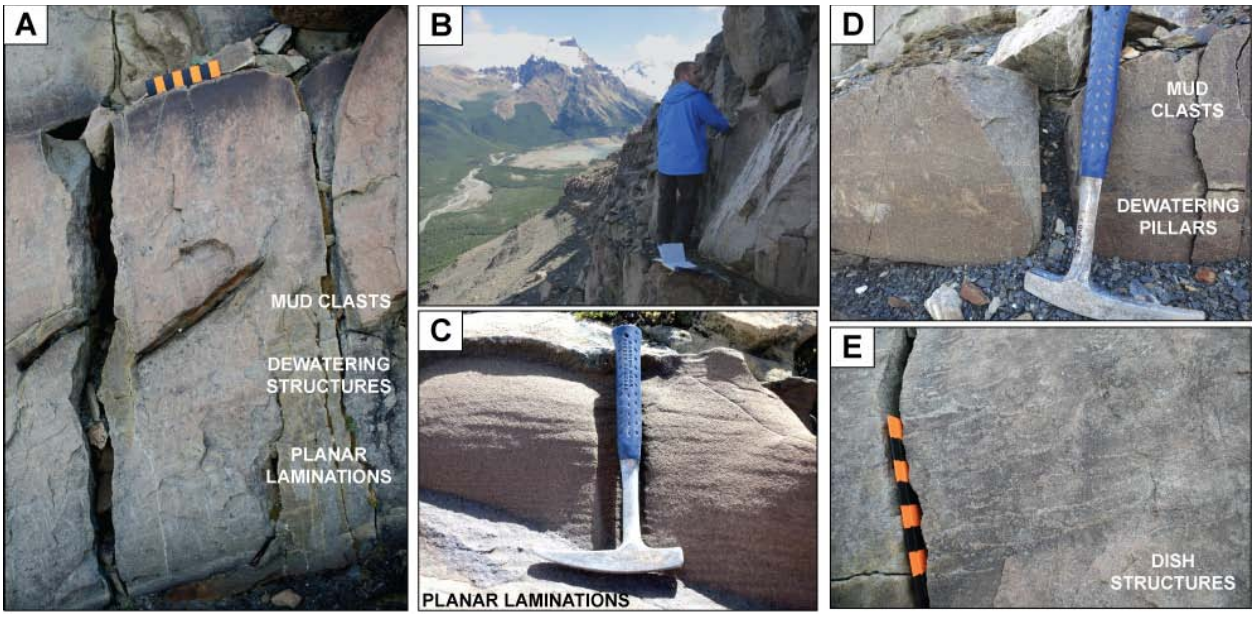


Figure 1.8. Examples of sedimentary structures and bedding characteristics of sandstone units from Loma de las Pizarras.

Notes:

STOP 3: View and discuss the Lago Viedma Formation, Cerro Pyramide

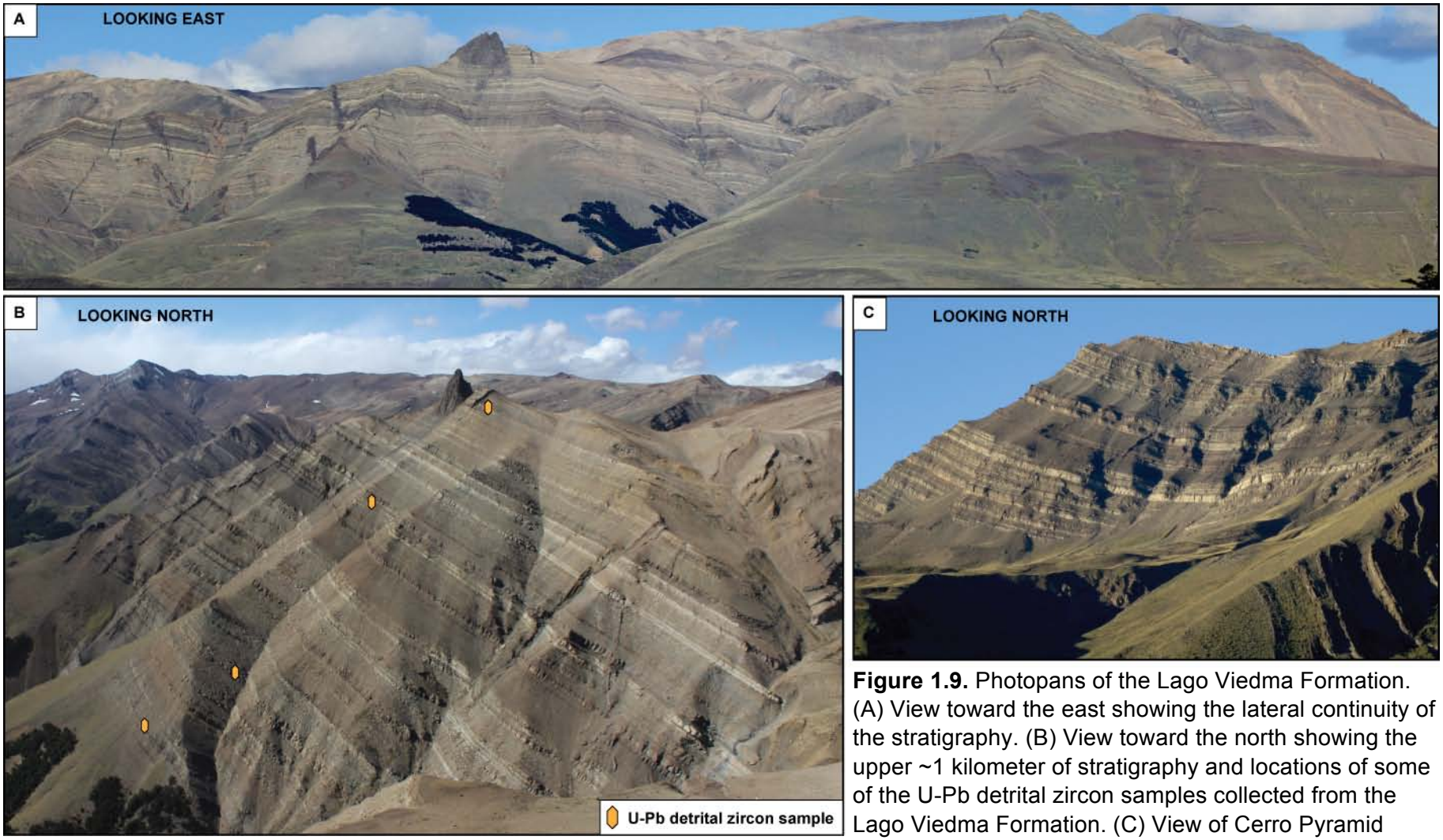


Figure 1.9. Photopans of the Lago Viedma Formation. (A) View toward the east showing the lateral continuity of the stratigraphy. (B) View toward the north showing the upper ~1 kilometer of stratigraphy and locations of some of the U-Pb detrital zircon samples collected from the Lago Viedma Formation. (C) View of Cerro Pyramid looking toward the north from the road into El Chalten.

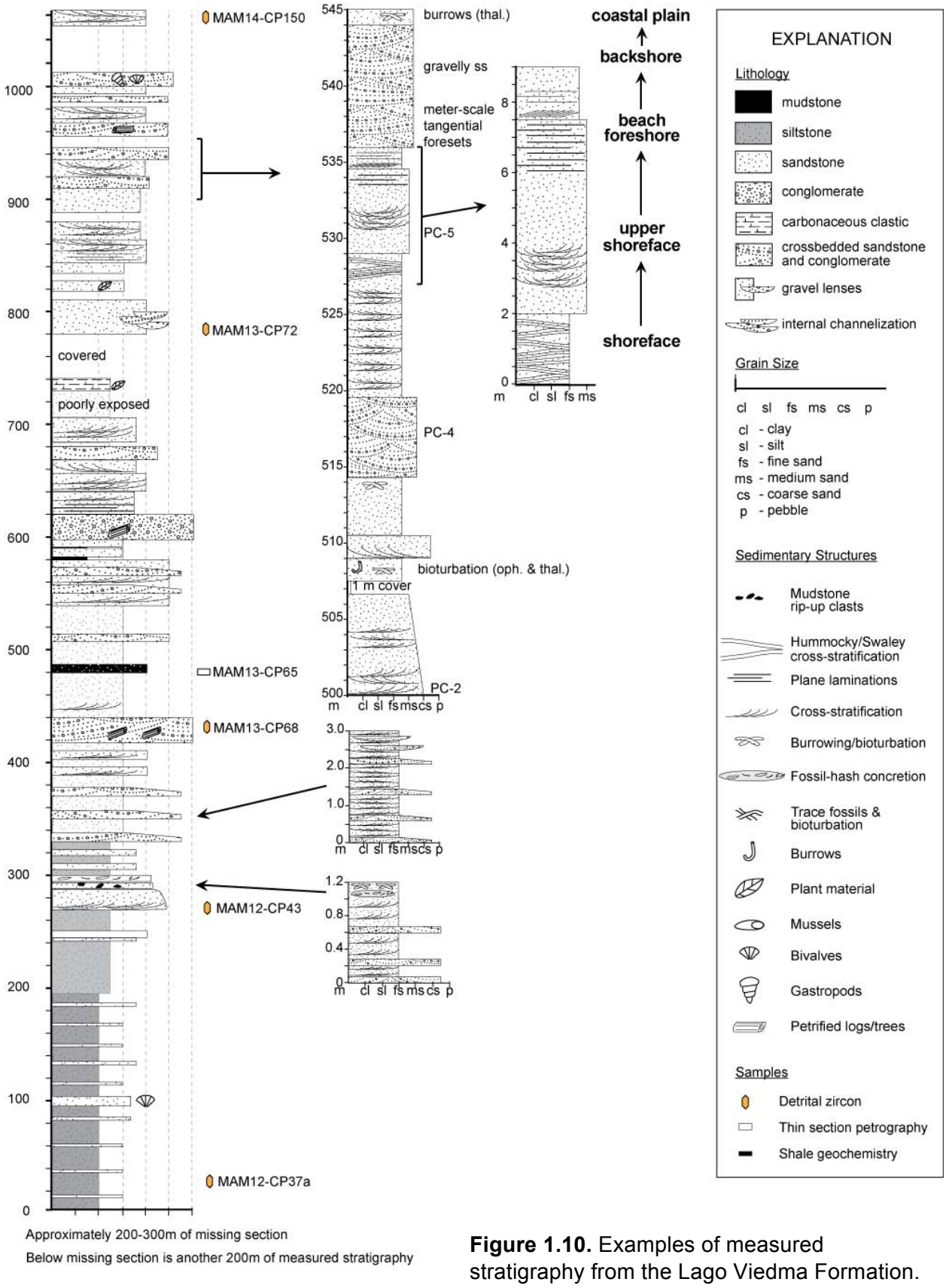


Figure 1.10. Examples of measured stratigraphy from the Lago Viedma Formation.

Figure 1.11. Examples of common sedimentary structures observed in the Lago Viedma Fm.

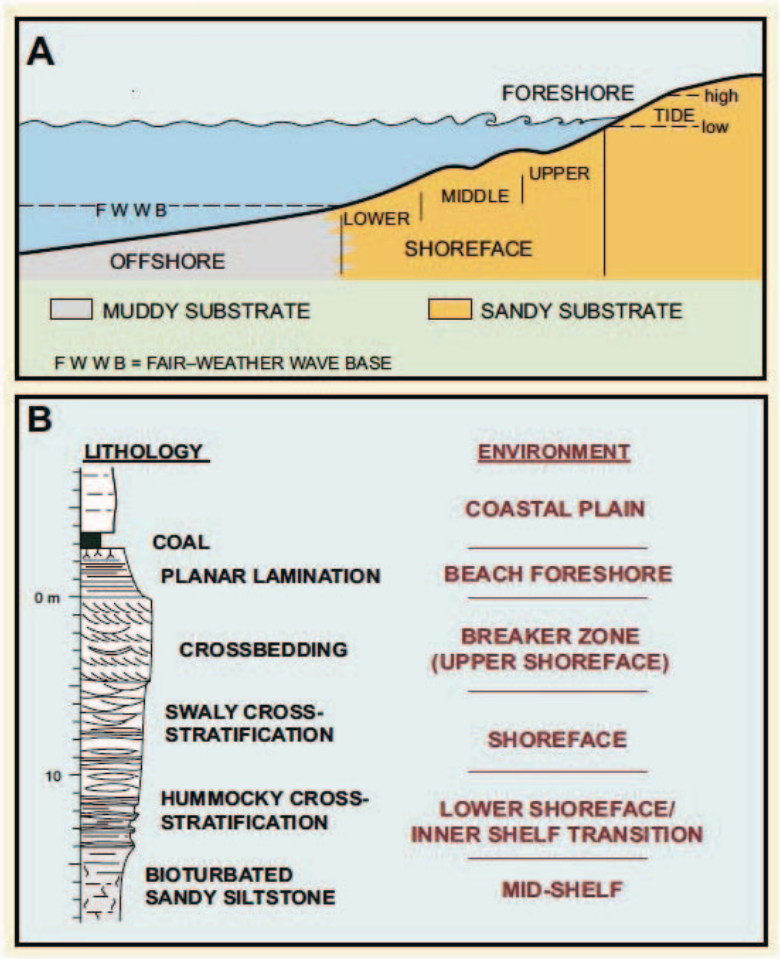


Figure 1.12. From Clifton (2006). (A) Beach-to-offshore profile in facies model of Walker and Plint (1992). Fair-weather wave base at base of shoreback. (B) Shallowing-up facies succession in facies model of Walker and Plint (1992).

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DAY 2 – Tuesday, 3 March 2015

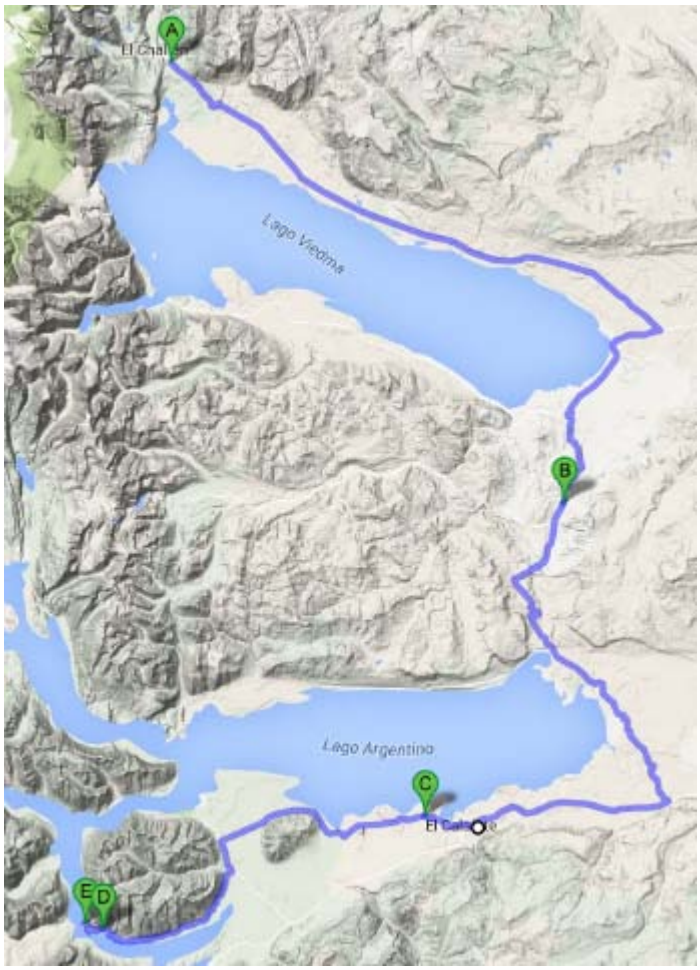
Destination: El Calafate, Magallanes Peninsula, Glaciar Perito Moreno

Today will primarily be used for driving from El Chaltén to El Calafate and the Magallanes Peninsula. We will depart from Estancia La Quinta **no later than 8:00 a.m**.

On the way to El Calafate, we will be driving through exposures of shallow marine and slope facies of variable age. As we drive east out of El Chaltén, we will drive through heavily deformed, Magallanes-Austral basin fill that becomes progressively younger and less-deformed to the east. As we near RN40, you will notice flat-topped mesas capped by basalt. Basalt extrusion is interpreted to be related to subduction of the Chile ridge in Neogene time.

We will make two stops on the way to the Magallanes Peninsula to discuss exposures of Upper Cretaceous shallow marine and slope deposits, as well as the regional Paleocene unconformity. These stops will occur at turnoffs between Lagos Viedma and Argentino, and then at a turnoff just west of El Calafate (also a lunch stop). We will then continue west and drive to the Magallanes Peninsula, where we will see deep-water lobe deposits of the Punta Barrosa Formation. We will end the day by viewing the Perito Moreno Glacier in Parque Nacional los Glaciares.

Driving Directions: Estancia La Quinta to El Calafate and the Magallanes Peninsula (approx. 5.5 hours total driving time)



1. Head **east** from **Ea. La Quinta** on **RP23** .....84.9 km
2. Turn **right (south)** on **RN40**, toward El Calafate .....~35 km
    a. **Stop 2-1**: Shallow-marine facies and the Paleocene unconformity at Co. Fortaleza
3. Continue **south** on **RN40** .....~60 km
4. Turn **right (west)** on **RP11**, toward El Calafate .....28.2 km
5. At the first roundabout, continue **straight** to stay on **RP11** .....2.0 km
6. Keep **left** to continue on **Av del Libertador San Martin** .....1.2 km
7. Turn **right** at **Amado** ..... 57 m
8. Turn **left** onto **Sarmiento** ..... 82 m
9. **Continue** onto **Av del Libertador San Martin** .....4.2 km
10. **Continue** onto **RP11** .....~2 km
    a. **Stop 2-2**: Lunch. Shallow marine facies at Cerro Calafate.
11. Continue **west** on **RP11** .....68.8 km
    a. **Stop 2-3**: Deep-water lobe deposits of the Punta Barrosa Formation.
12. Continue **west** on **RP11** toward Perito Moreno Glacier .....4.9 km
    a. **Stop 2-4**: Perito Moreno Glacier and visitor center.
13. **Return to Calafate** and check into the **Hotel Mirador del Lago** on **Av del Libertador San Martin, #2047**.

Accommodations (3 March): Hotel Mirador del Lago, El Calafate.

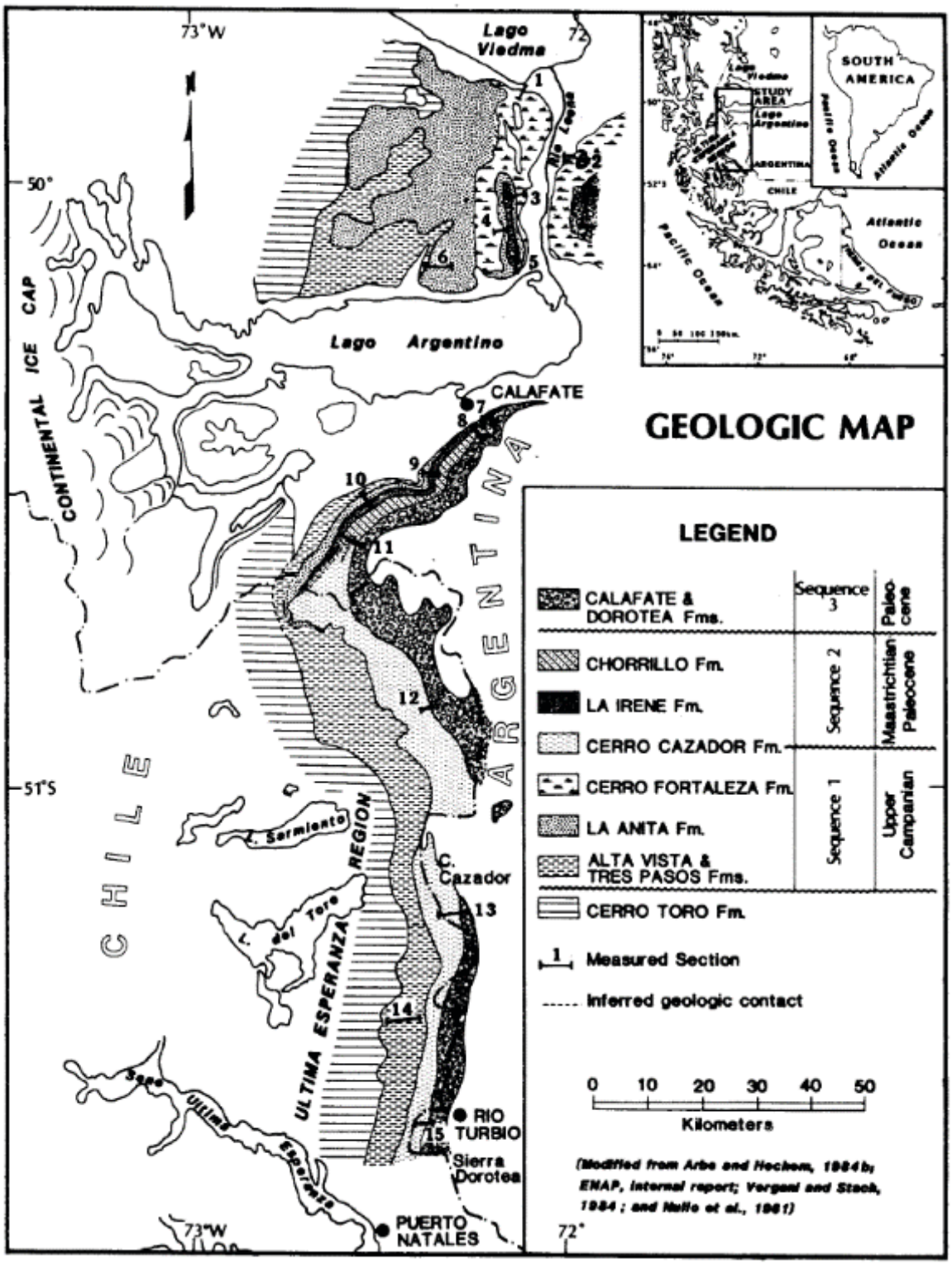


Figure 2.1. Geologic map of Upper Cretaceous stratigraphy adjacent to Lago Argentino (from Macellari et al., 1989).

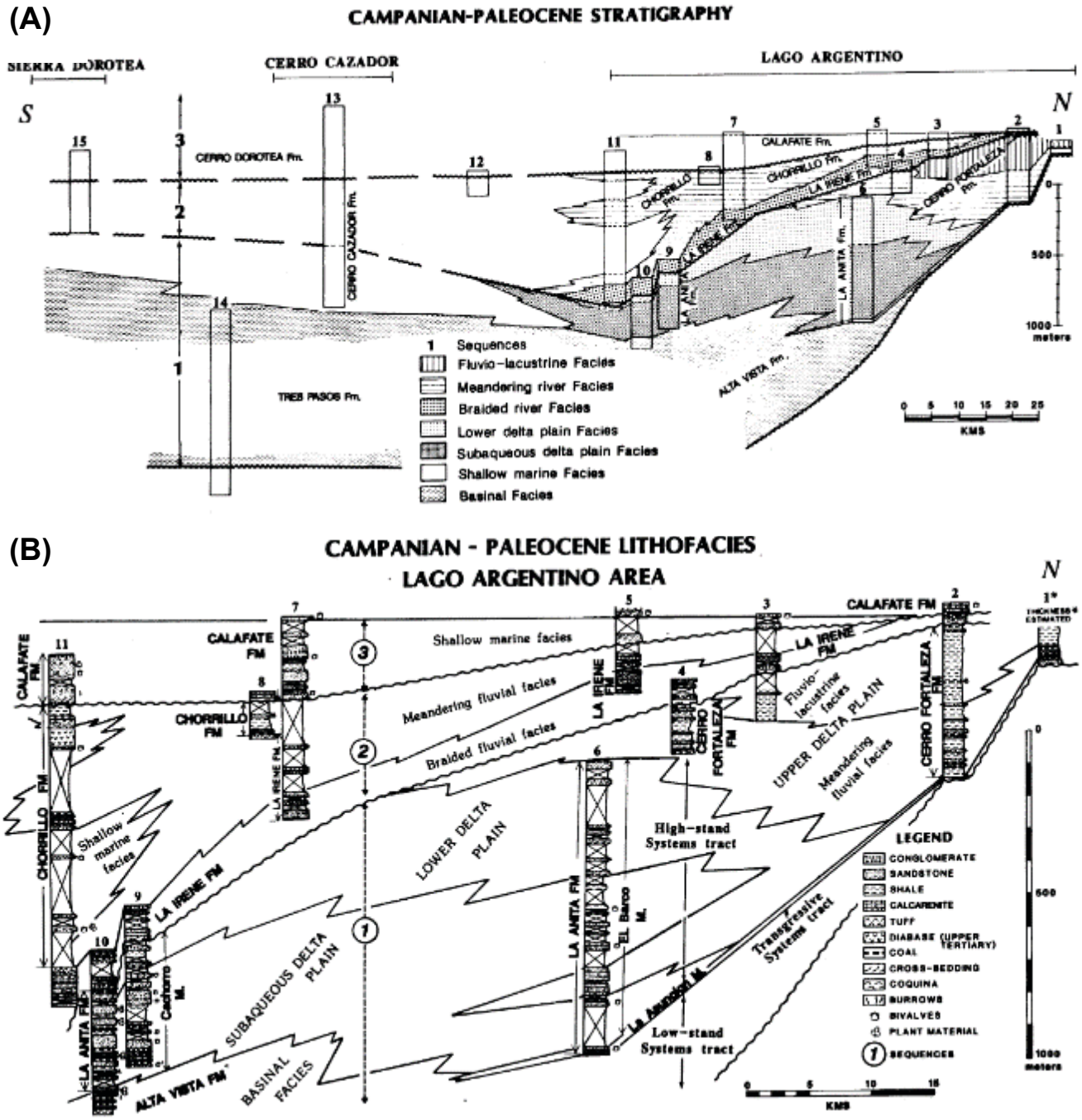


Figure 2.2. (A) North-to-South correlation of lithostratigraphic units presented in Figure 2.1. (B) Correlation of depositional facies in the Lago Argentino area (Macellari et al., 1989).

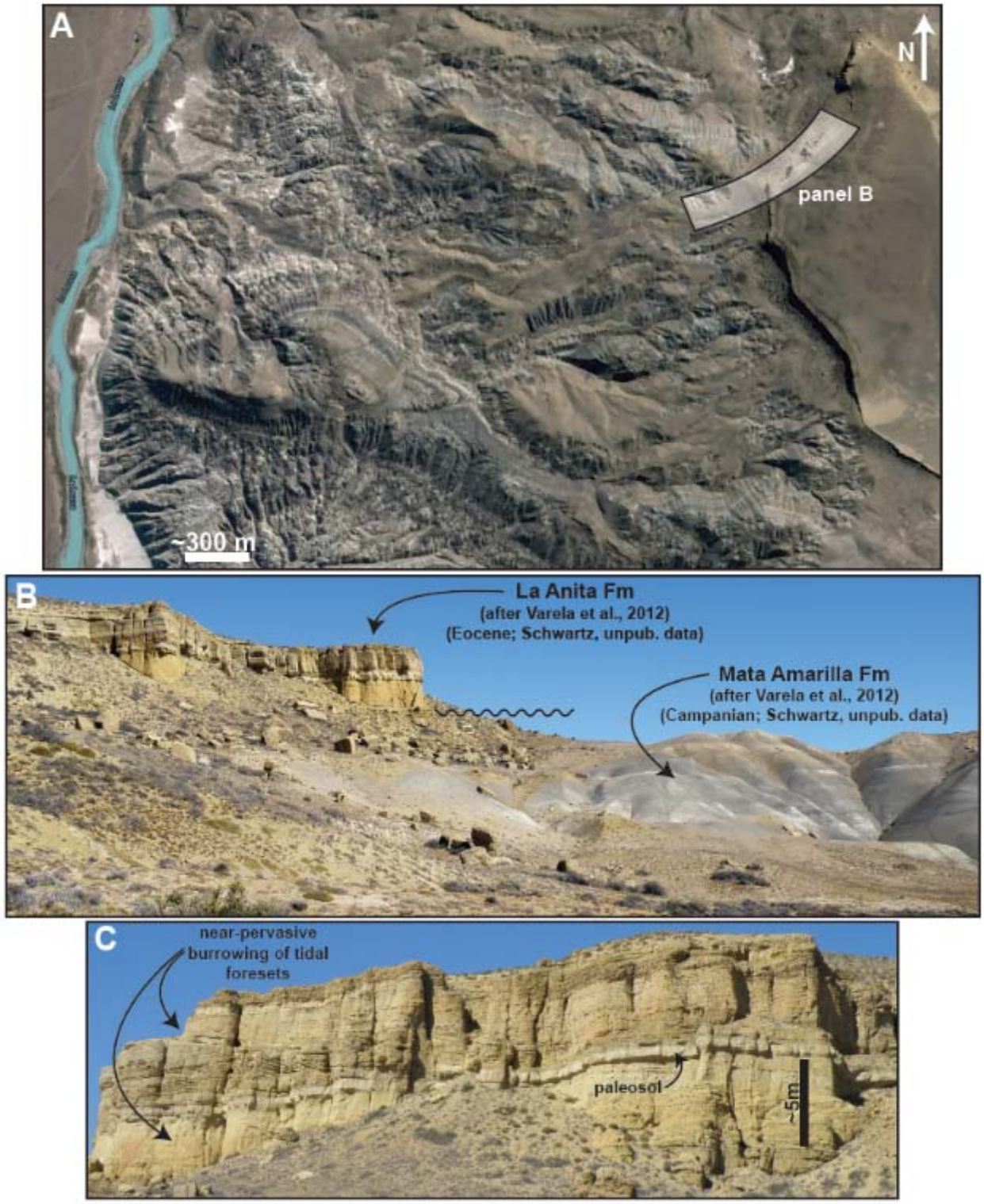


Figure 2.3. Exposures of the Paleocene unconformity at Co Fortaleza, west of Ruta 40. (A) Google Earth image of badlands topography typical of the Campanian Mata Amarilla Fm, capped by the resistant Eocene La Anita Fm. (B) Coastal plain deposits of the Mata Amarilla Fm unconformably overlain by tidally dominated shallow-marine deposits of the La Anita Fm. The

unconformity is very low-angle and obscured in outcrop, but is apparent in fossil and detrital zircon data. (C) Close-up of tidal architecture of the La Anita Fm. Photos by T. Schwartz.

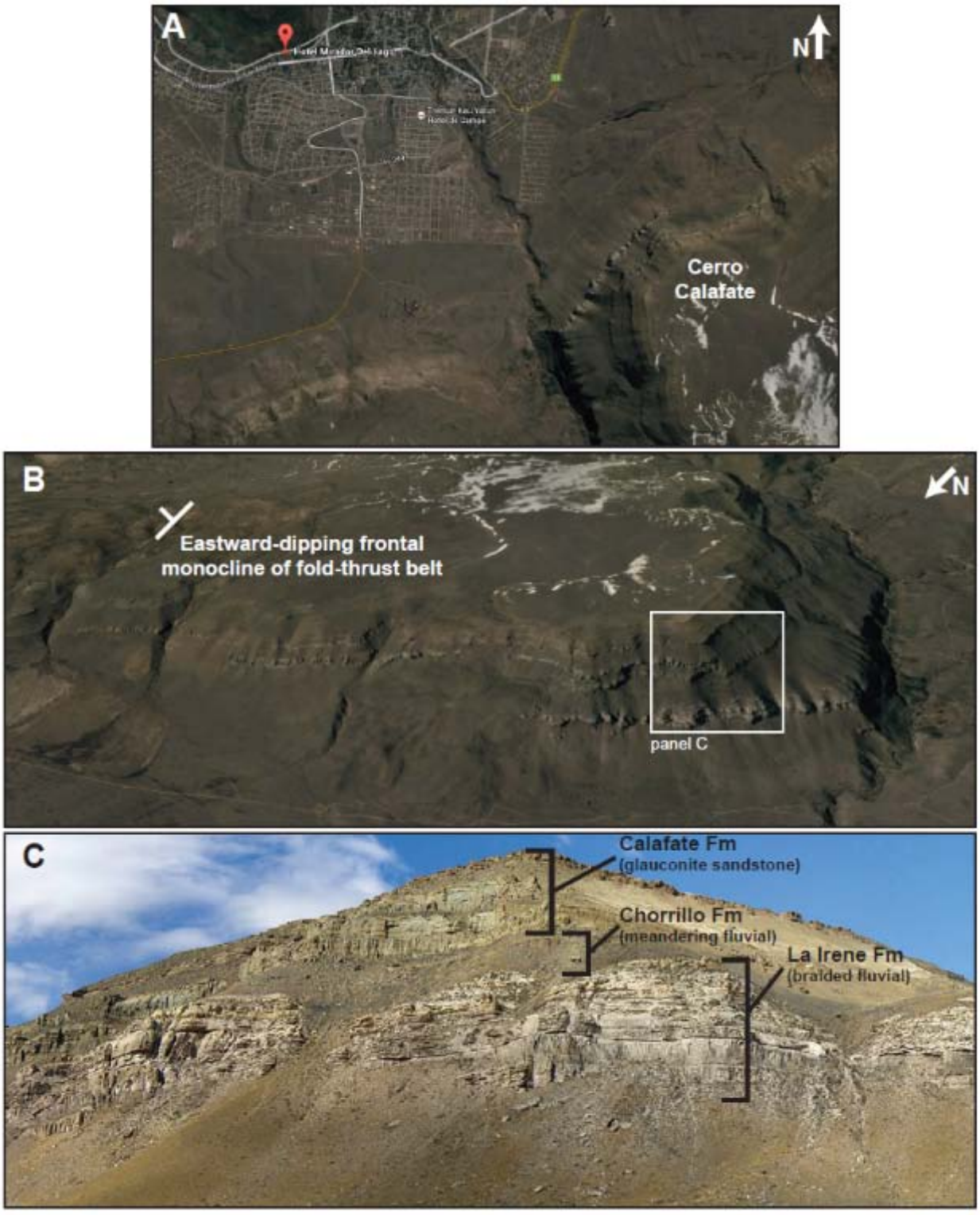


Figure 2.4. Upper Cretaceous shallow- to non-marine strata exposed on Cerro Calafate. (A) Google Earth image of El Calafate and Co Calafate. (B) Oblique Google Earth image of Co Calafate, illustrating monoclinal dip to the east. (C) Photograph of Co Calafate, displaying the La Irene, Chorrillo, and Calafate Formations (after Macellari et al., 1989; photo by T. Schwartz).

Figure 2.5. (A) Panorama looking toward the southeast of Cerro Calafate, including the La Irene, Corrillo, Calafate, and Man Aike Formations. Note that prominent green unit is highly glauconitic sandstone of the Calafate Formation (photo by M. Malkowski). (B) Panorama looking toward the south of the Alta Vista/Tres Pasos and Dorotea/Calafate Formations, which underlie the strata at Cerro Calafate. Preliminary work by Z. Sickmann indicates possible mass-failure in muddy facies (foreground, covered). Note upward coarsening and thickening of beds in cliffs, indicating shoreline progradation over muddy slope facies exposed on Cerro Cristales (see **Alternate Option #1** at end of field guide for details) (photo by T. Schwartz).

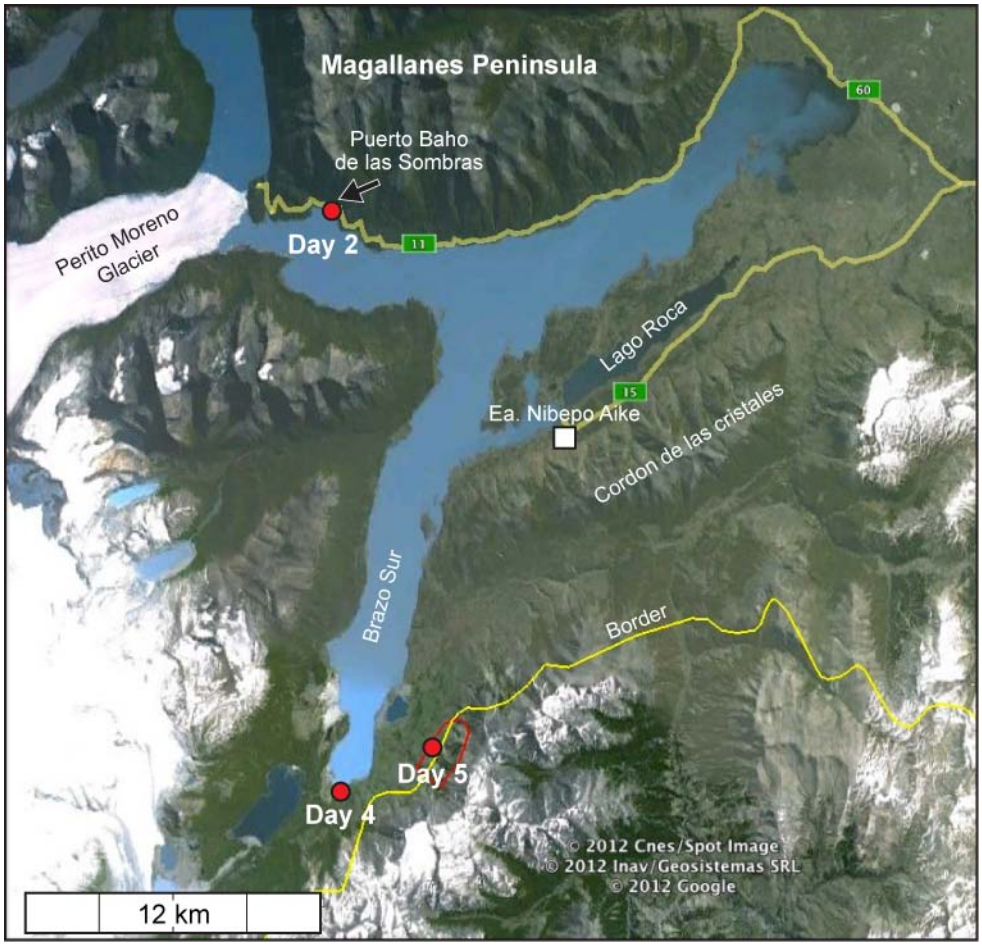
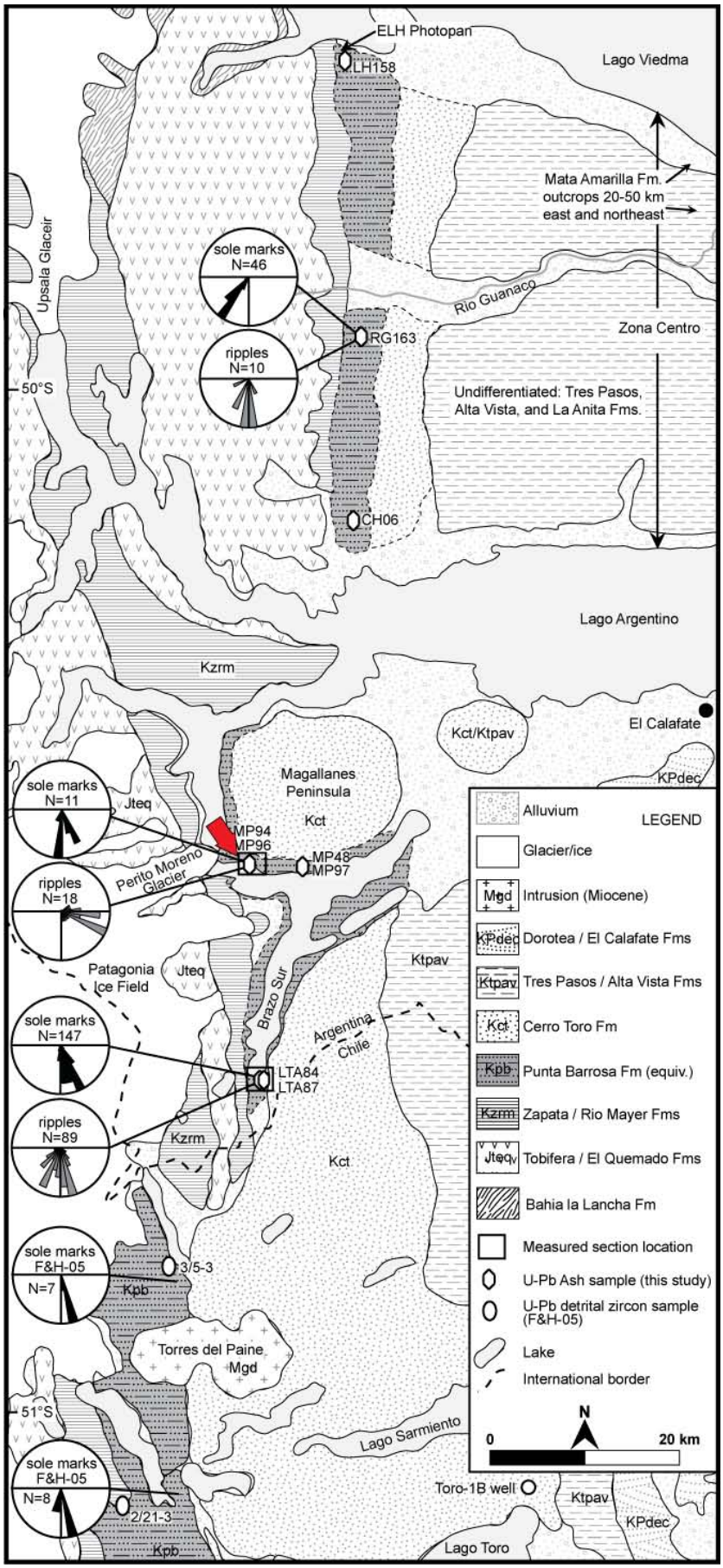


Figure 2.6. Google Earth satellite image of the Brazo Sur region. Day 2 involves a stop at the Puerto Baho de las Sombras to look at outcrops of the Punta Barrosa Formation equivalents.

Figure 2.7. Road cut exposure on the Magallanes Peninsula, along route 11, where ash sample MP48 (red polygon) and DZ sample MP97 (orange polygon) were collected. Rock hammer for scale. Data presented in posters.

Figure 2.8. (following page) Geologic map of Lago Argentino region (Malkowski et al., in review)


ELH Photopan
LH158
Lago Viedma
Mata Amarilla Fm.
outcrops 20-50 km
east and northeast
Upsala Glacier
sole marks
N=46
Rio Guanaco
RG163
Zona Centro
ripples
N=10
50°S
Undifferentiated: Tres Pasos,
Alta Vista, and La Anita Fms.
CH06
Lago Argentino
Kzrm
El Calafate
Kct/Ktpav
KPdec
Magallanes
Peninsula
sole marks
N=11
Jteq
Kct
MP94
MP96
MP48
MP97
Perito Moreno
Glacier
ripples
N=18
Patagonia
Ice Field
Jteq
Ktpav
Brazo Sur
sole marks
N=147
Argentina
Chile
LTA84
LTA87
ripples
N=89
Kzrm
Kct
sole marks
F&H-05
N=7
3/5-3
Kpb
Torres del Paine
Mgd
51°S
Lago Sarmiento
sole marks
F&H-05
N=8
2/21-3
Kpb
Toro-1B well
Ktpav
KPdec
Lago Toro
LEGEND
Alluvium
Glacier/ice
Mgd
Intrusion (Miocene)
KPdec
Dorotea / El Calafate Fms
Ktpav
Tres Pasos / Alta Vista Fms
Kct
Cerro Toro Fm
Kpb
Punta Barrosa Fm (equiv.)
Kzrm
Zapata / Rio Mayer Fms
Jteq
Tobifera / El Quemado Fms
Bahia la Lancha Fm
Measured section location
U-Pb Ash sample (this study)
U-Pb detrital zircon sample
(F&H-05)
Lake
International border
N
0
20 km

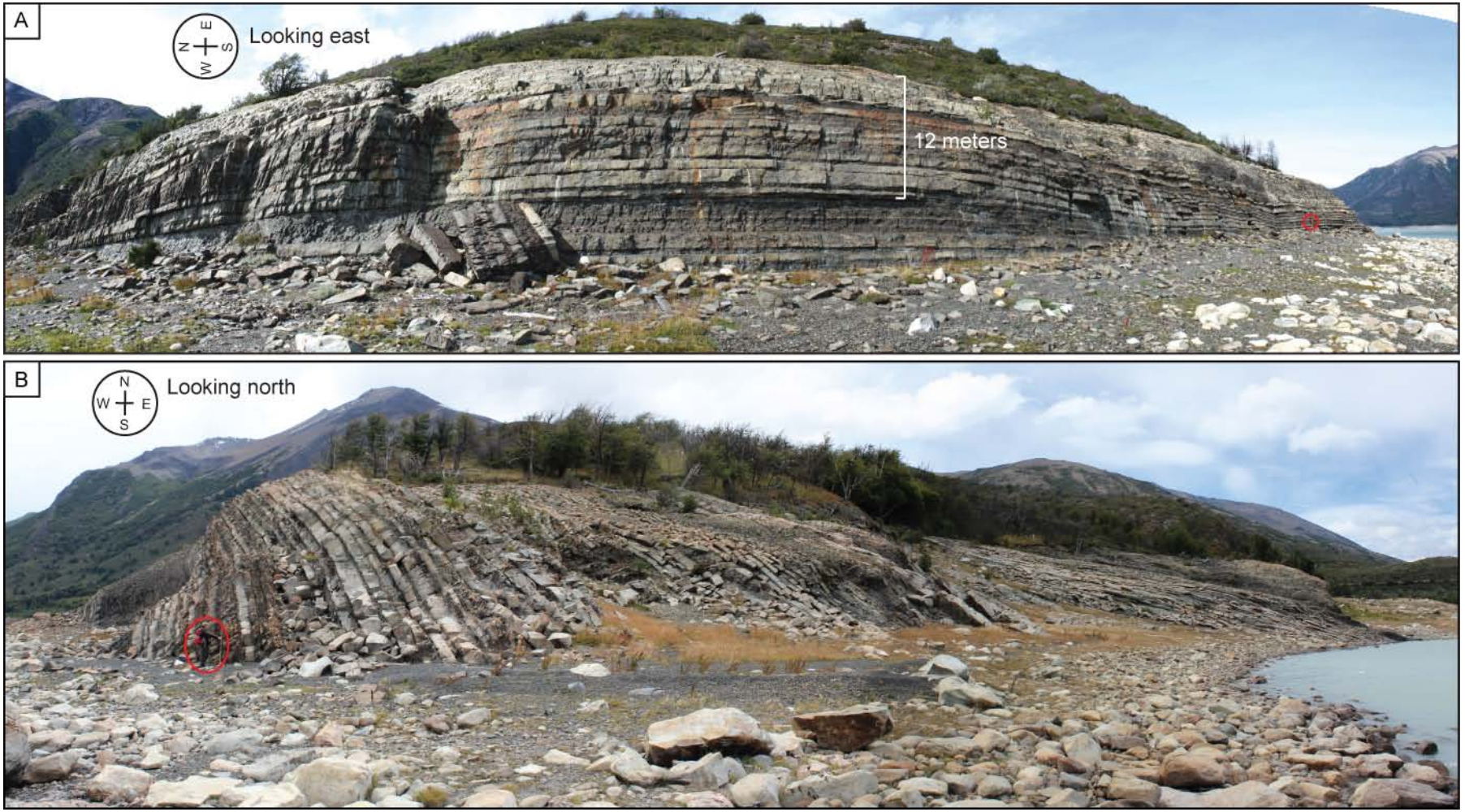


Figure 2.9. Photopans of the stratigraphy near Puerto Baho de las Sambras representing Punta Barrosa equivalent units. (A) View toward the east highlighting the lateral continuity of beds (from Malkowski et al., in review). (B) View toward the north show the profile image of the measured stratigraphy in Figure 2.10. Person for scale (red circle) in both photos.

Figure 2.10. (following page) Measured section of the Punta Barrosa Fm. near Puerto Baho de las Sambras (Malkowski et al., in review)

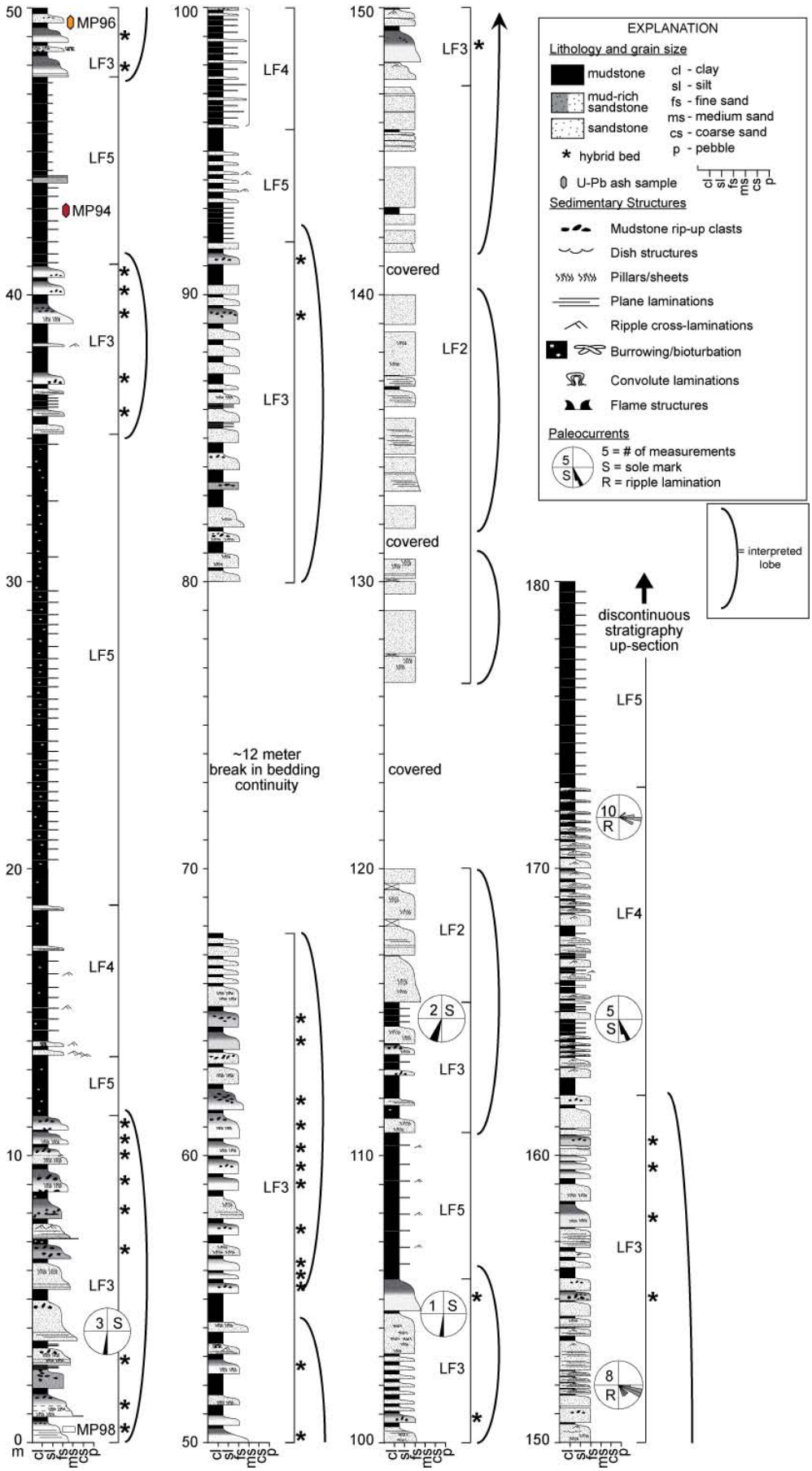

EXPLANATION
Lithology and grain size
mudstone
mud-rich sandstone
sandstone
cl - clay
sl - silt
fs - fine sand
ms - medium sand
cs - coarse sand
p - pebble
* hybrid bed
U-Pb ash sample
Sedimentary Structures
Mudstone rip-up clasts
Dish structures
Pillars/sheets
Plane laminations
Ripple cross-laminations
Burrowing/bioturbation
Convolute laminations
Flame structures
Paleocurrents
5 = # of measurements
S = sole mark
R = ripple lamination
= interpreted lobe
MP96
MP94
MP98
LF3
LF4
LF5
LF2
covered
~12 meter break in bedding continuity
discontinuous stratigraphy up-section
m
cl sl fs ms cs p

Figure 2.11. Various examples of trace fossils found within the Punta Barrosa Formation along the Magallanes Peninsula. *Ophiomorpha (O), Thalassinoides (Th), Skolithos (S), Spirophyton (Sp), Scolicia (Sc), Cosmorhaphe (Cr).*

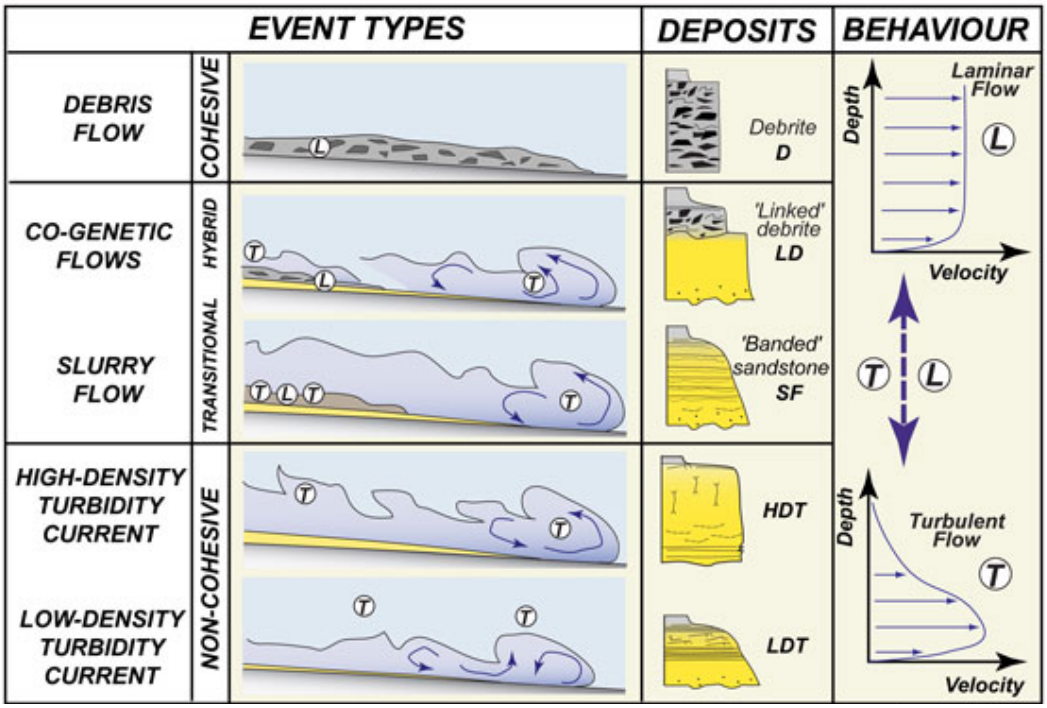


Figure 2.12. From Haughton et al (2009) – classification scheme of various types of sediment gravity flow deposits and associated behavior.

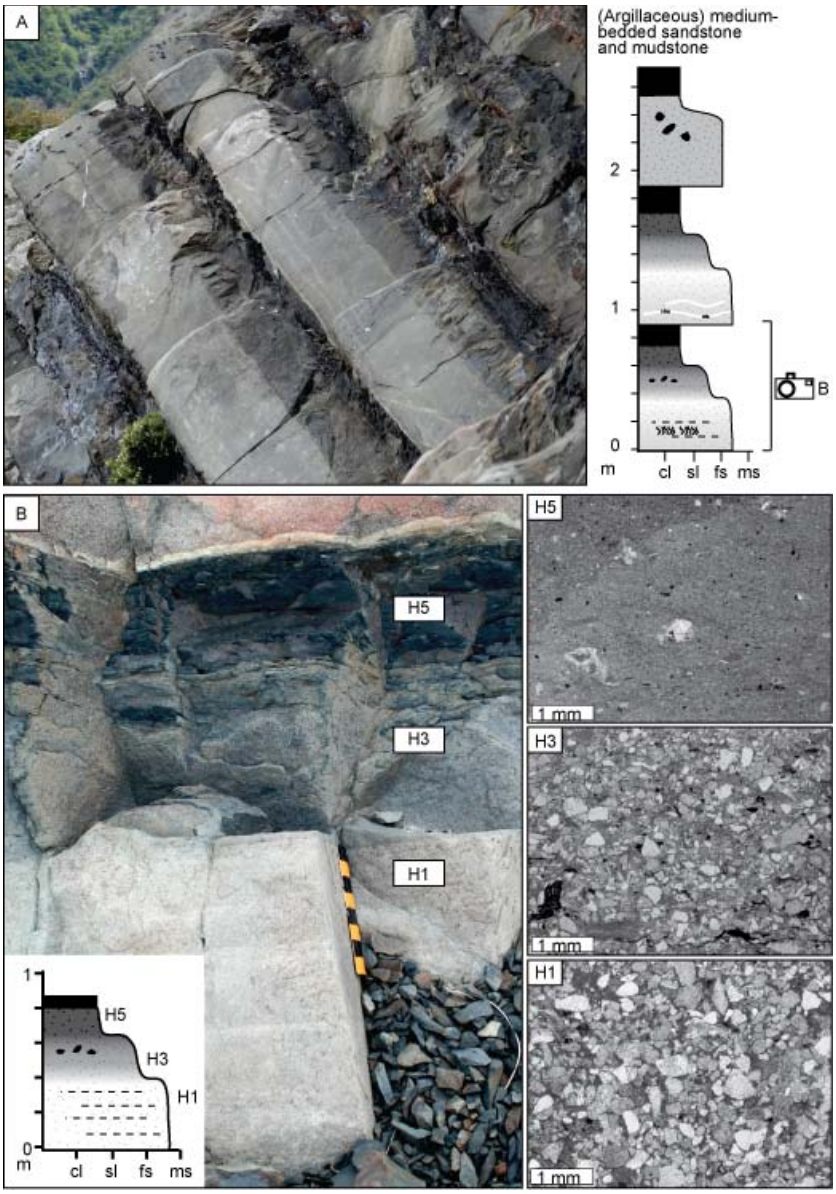


Figure 2.13. Characteristics of hybrid beds from the Magallanes Peninsula. A) Representative bed-scale characteristics of multiple hybrid beds, which are commonly associated with LF-3. See section adjacent to photo for scale. B) Example of within-bed features showing abrupt changes in color and inferred detrital mud content. Locations of thin section photomicrographs identified as H1, H3, and H5 (after Haughton et al., 2009). Although sand-sized grains are present throughout, the apparent abundance of mud concentration increases upward in the bed.

DAY 3 – Wednesday, 4 March 2015

Destination: Estancia Cristina

Today will begin with a boat ride to Estancia Cristina, on the northwest shore of Lago Argentino, from Puerto Bandera. At Estancia Cristina, we will have a day hike to see outcrops of the predecessor Rocas Verdes basin fill. Departure times are TBD.

Driving Directions: Hotel Mirador del Lago to Puerto Bandera (boat launch; approx. 1 hour driving time)

1. Head **west** on **Av del Libertador San Martin** toward **Calle 91** .....2.8 km
2. Continue onto **RP11**.....34.9 km
3. Continue straight onto **RP8**.....8.8 km
4. Park at boat launch.

Accommodations (4 March): Hotel Mirador del Lago, El Calafate.

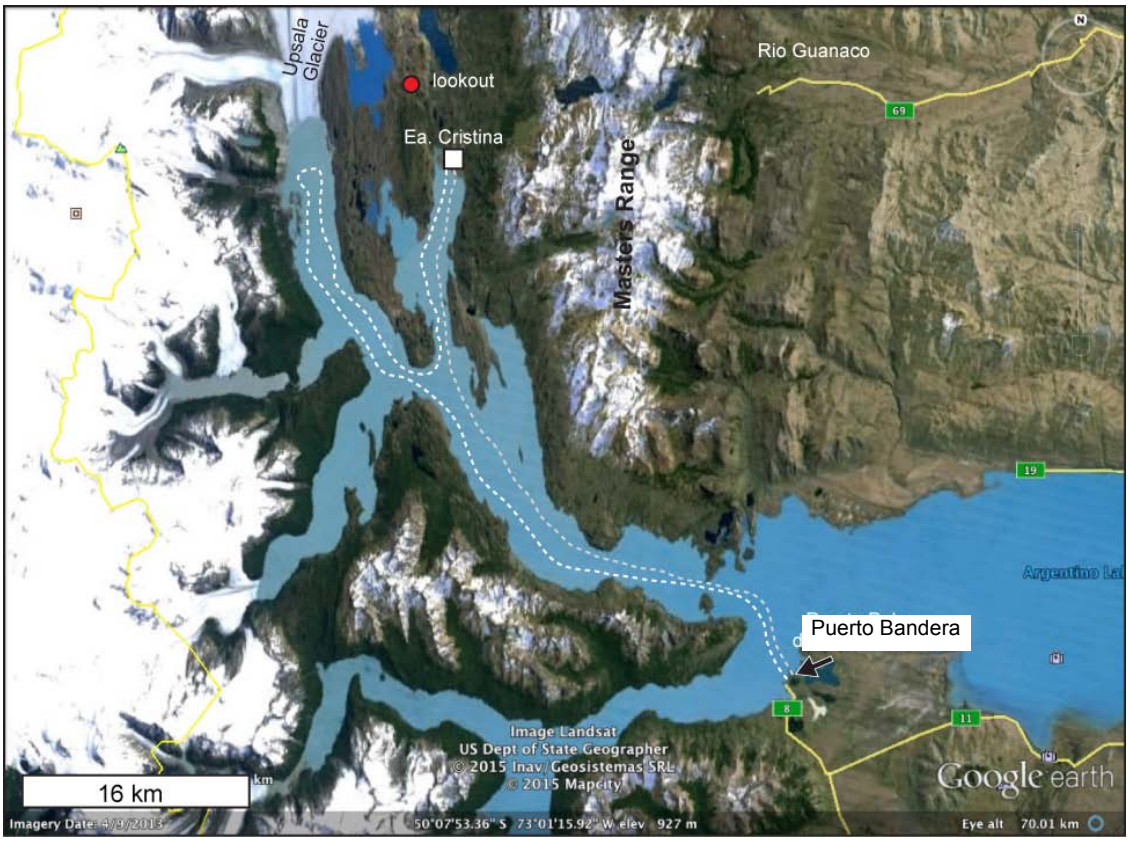


Figure 3.1. GoogleEarth satellite view of the region northwest of Lago Argentino, including boat route to Estancia Cristina.

Figure 3.2. (A) GoogleEarth satellite view of the terrain near the Upsala Glacier lookout at Estancia Cristina. Here, the contact between the El Quemado Complex and the Rio Mayer Formation is exposed along a southward plunging syncline at the Upsala Glacier lookout. (B) GoogleEarth satellite view toward the south along the western limb of the syncline exposing the transition from the El Quemado Complex (EQC) to the lower (LRM) and upper (URM) Rio Mayer Formation.

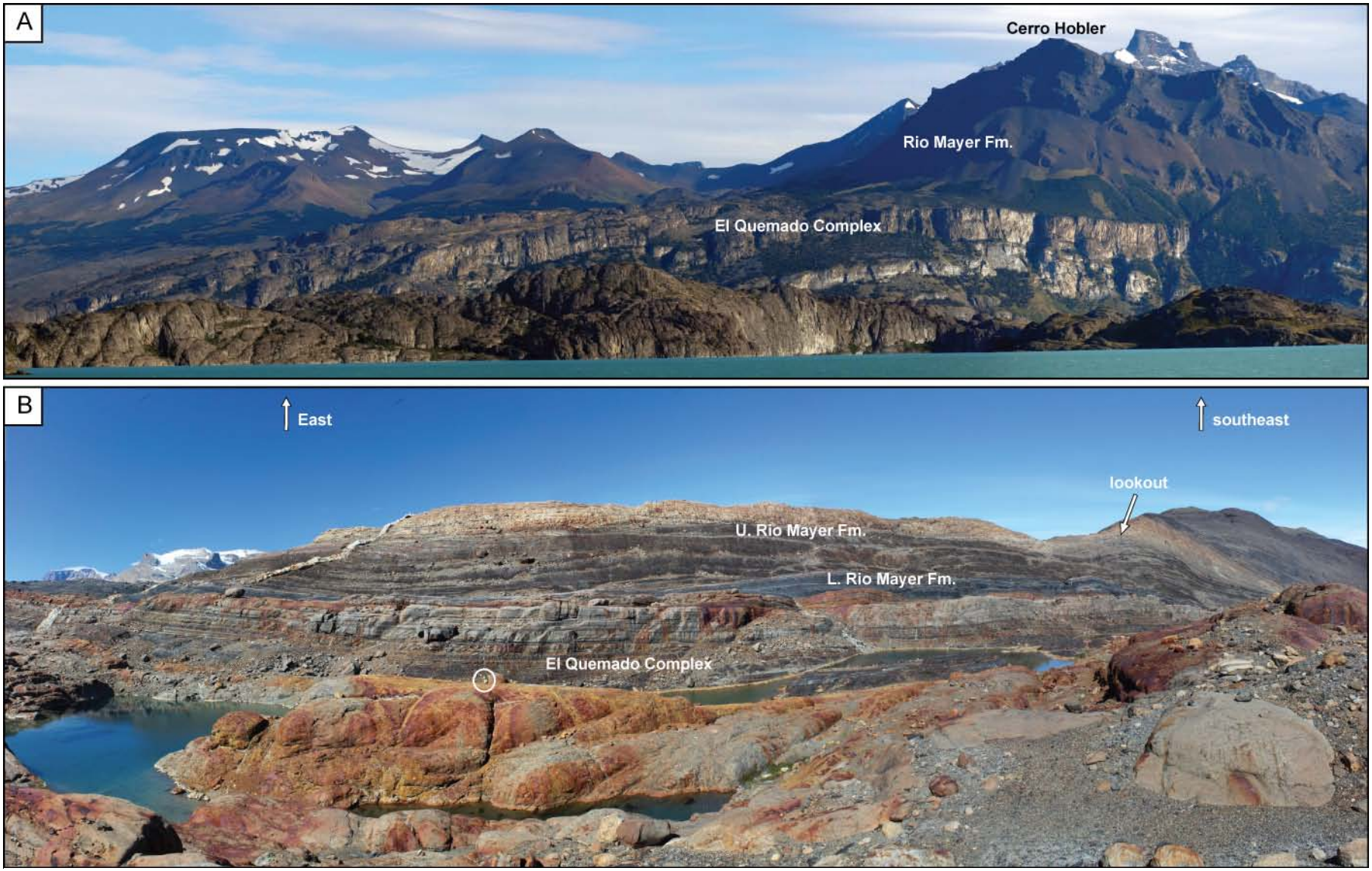


Figure 3.3. (A) Looking north at a large antiform on the northwest shore of Lago Argentino incorporating the Jurassic El Quemado Fm and Jurassic-Early Cretaceous Rio Mayer Fm (Photo by T. Schwartz). (B) Panoramic view to east/southeast of the stratigraphy exposed at the Upsala Glacier lookout near Estancia Cristina.

MEASURED STRATIGRAPHY:

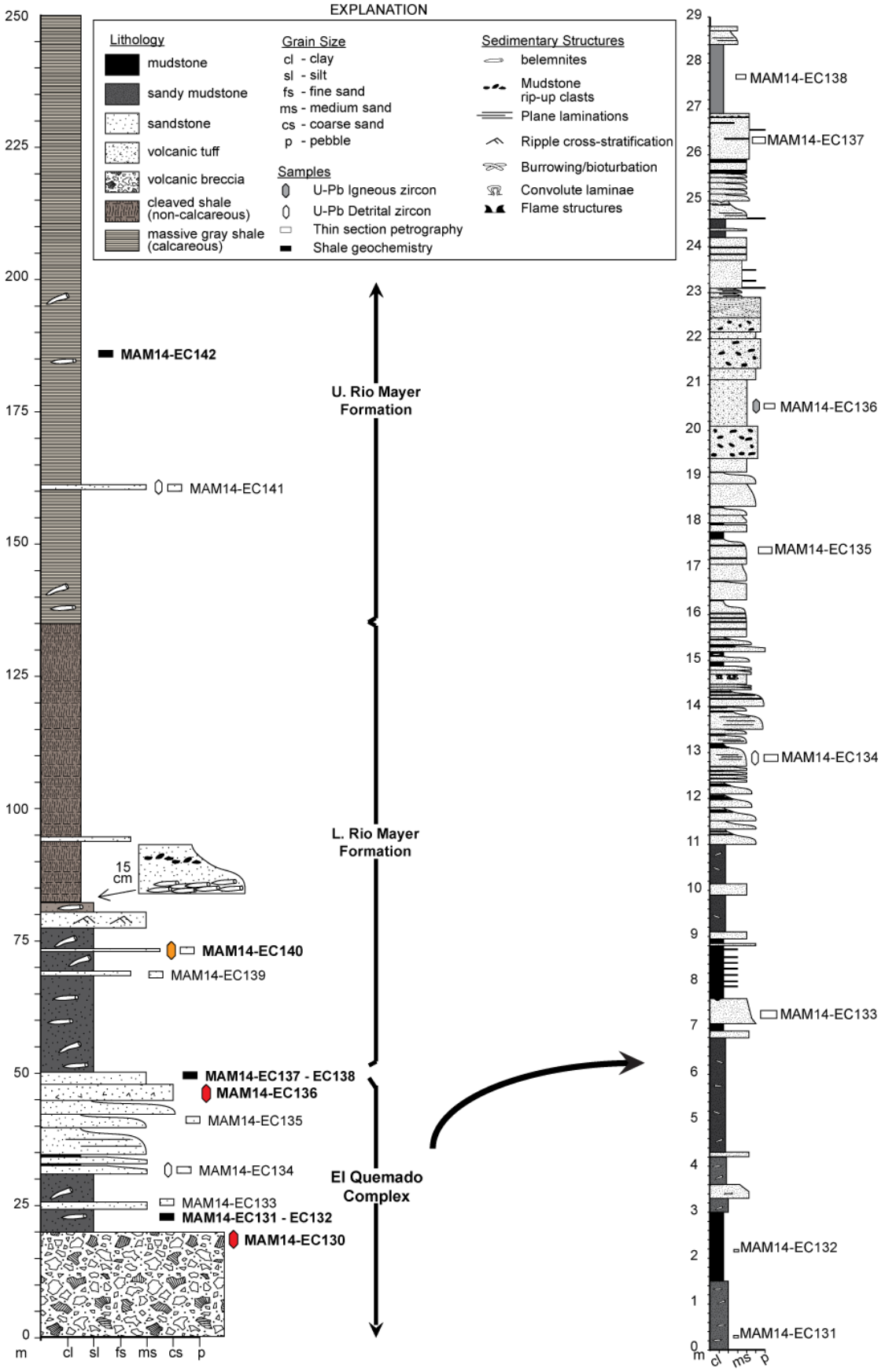


Figure 3.4. (previous page) Measured stratigraphic sections of the Jurassic El Quemado Complex through the Early Cretaceous Rio Mayer Formation exposed at Estancia Cristina (see Figure 3.3). Note that this section does not include the upper limits of the Rio Mayer Formation.

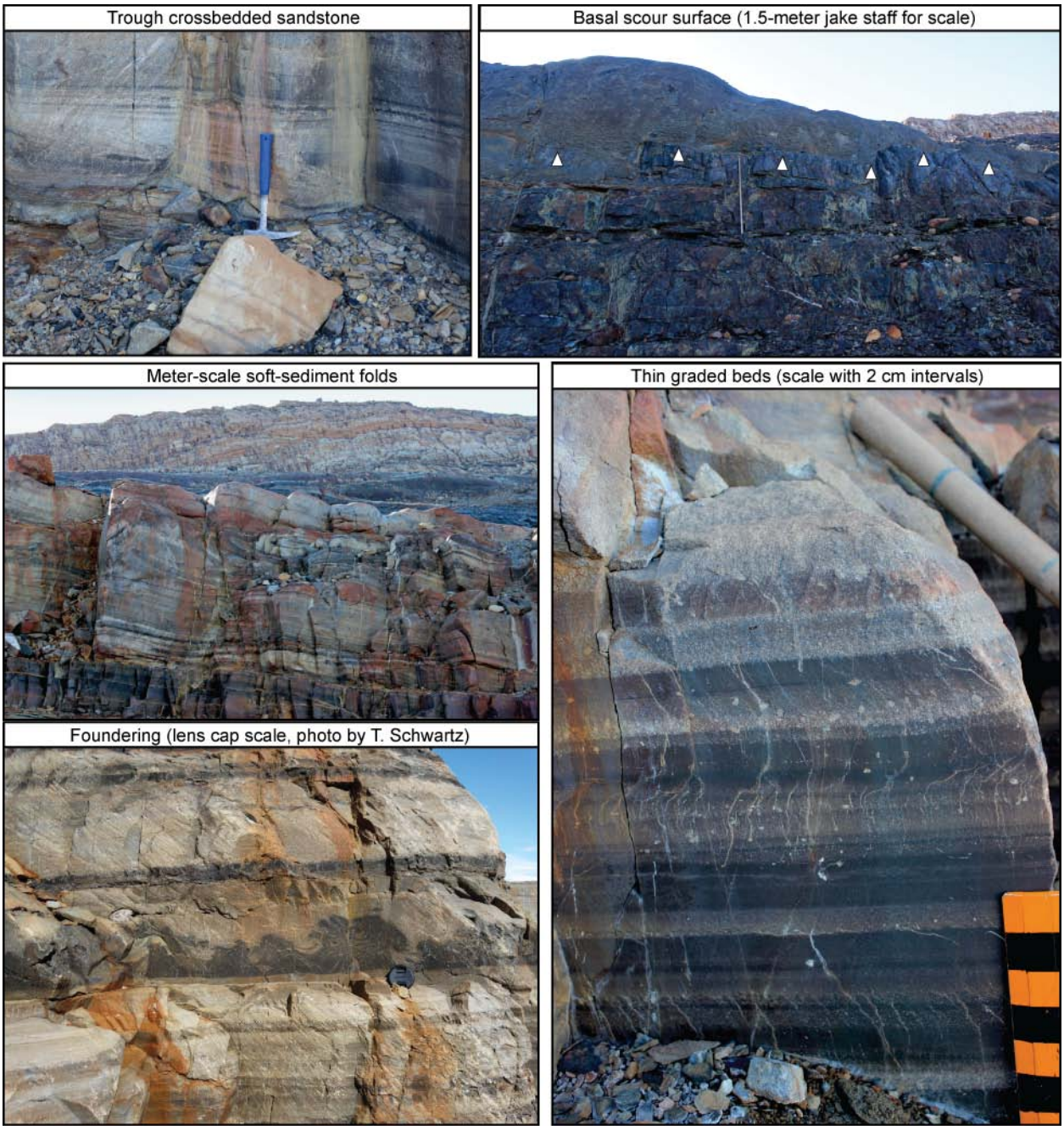


Figure 3.5. Outcrop photos showing the various sedimentological characteristics of the Spring Hill and Rio Mayer Formations.

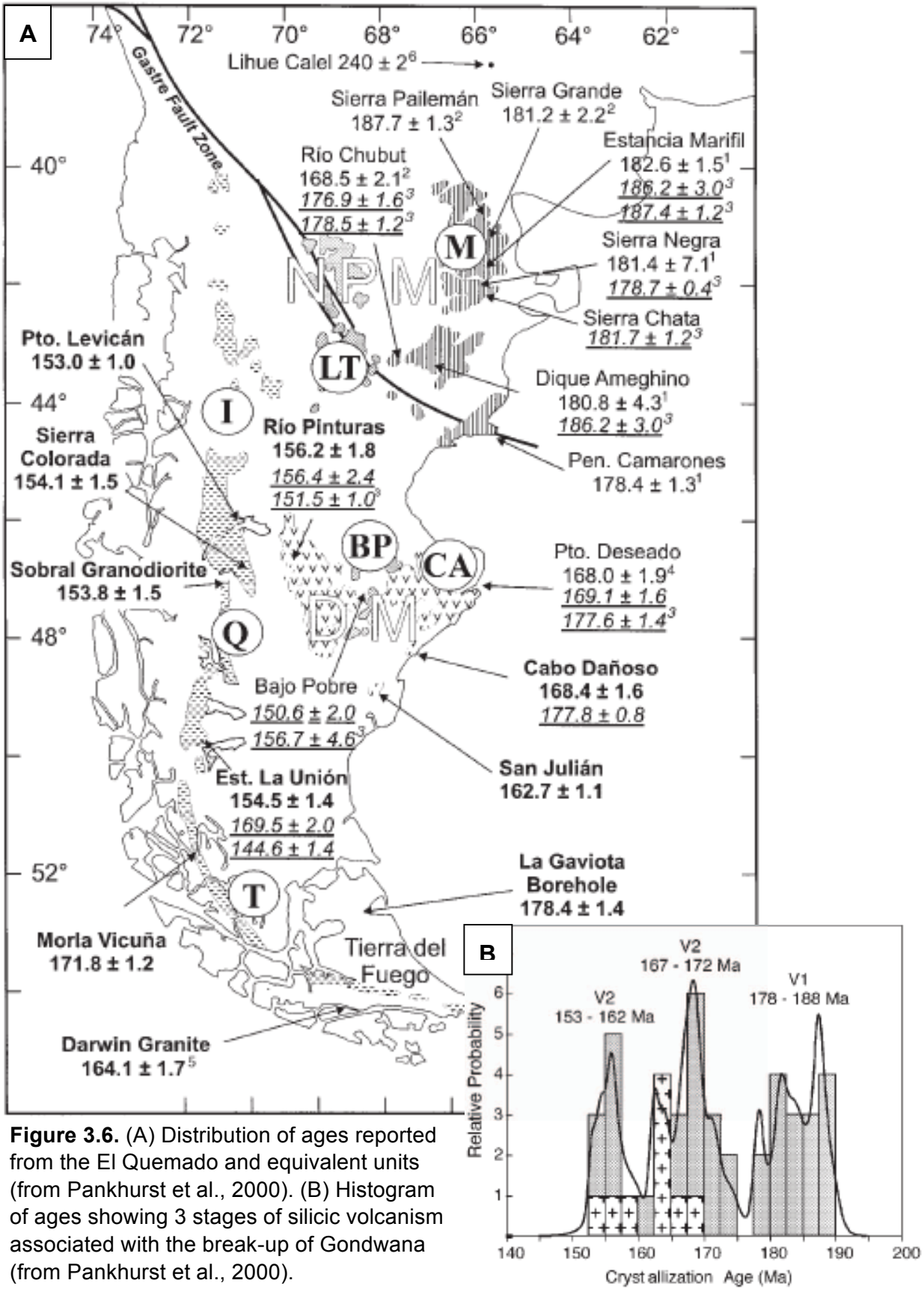


Figure 3.6. (A) Distribution of ages reported from the El Quemado and equivalent units (from Pankhurst et al., 2000). (B) Histogram of ages showing 3 stages of silicic volcanism associated with the break-up of Gondwana (from Pankhurst et al., 2000).

DAY 4 – Thursday, 5 March 2015

Destination: Punta Barrosa Formation on Brazo Sur de Lago Argentino

Today will consist of a boat ride from Estancia Nibepo Aike, near Lago Roca, to the southern end of the Brazo Sur de Lago Argentino. On the outcrop, we will use the day to investigate outcrops of lobe deposits of the Punta Barrosa Formation. Departure times are TBD.

Driving Directions: Hotel Mirador del Lago to Estancia Nibepo Aike (approx. 2 hours driving time)

1. Head **west** on **Av del Libertador San Martin** toward **Calle 91** ..... 54 m
2. Take **first left** onto **Calle 91** ..... 12 m
3. Take **first left** onto **Av del Libertador San Martin** ..... 120 m
4. Take **first right** onto **Napoleon Irusta** ..... 250 m
5. Turn **left** onto **Av Juan Domingo Peron** ..... 230 m
6. Turn **right** onto **Comodoro Luis Piedrabuena** ..... 450 m
7. Turn **right** onto **Av 17 de Octubre** .....1.7 km
8. Continue onto **RP15**.....50.4 km
9. Park in designated Estancia Nibepo Aike parking lot.

Accommodations (5 March): Hotel Mirador del Lago, El Calafate.

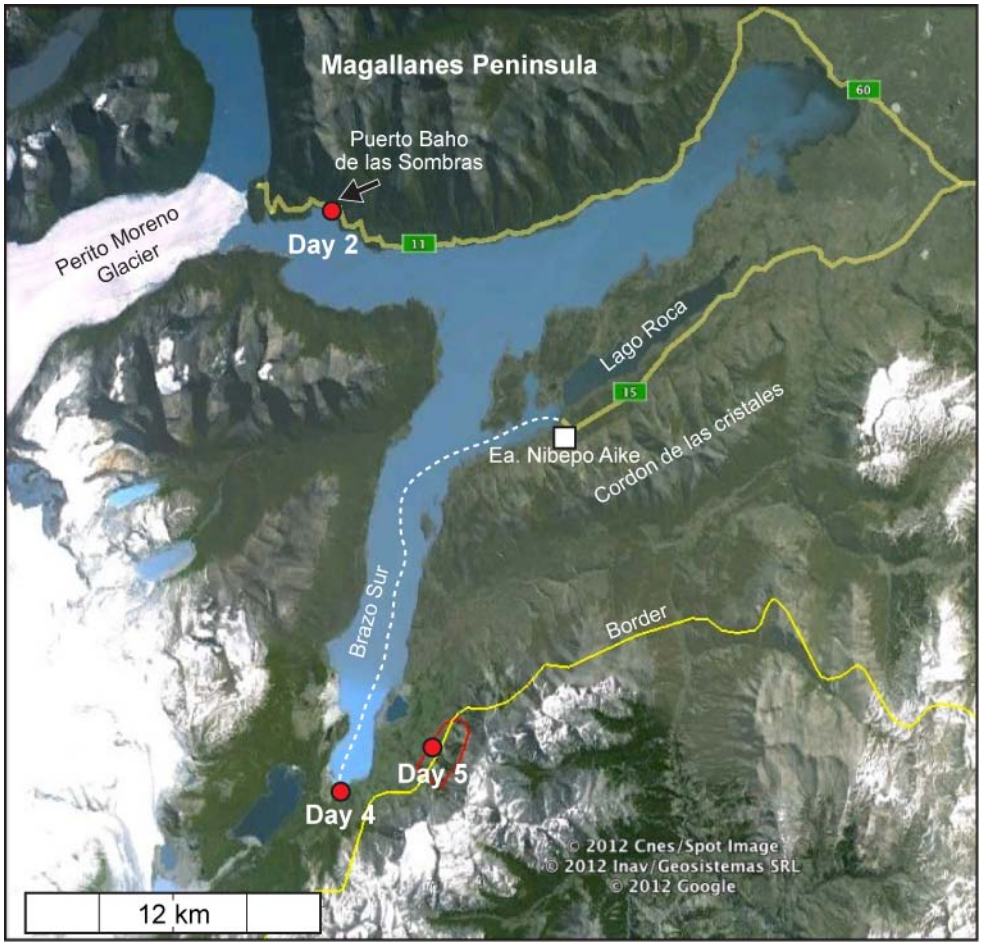


Figure 4.1. GoogleEarth satellite view of the Brazo Sur region. See Figure 2.8 for geologic map.

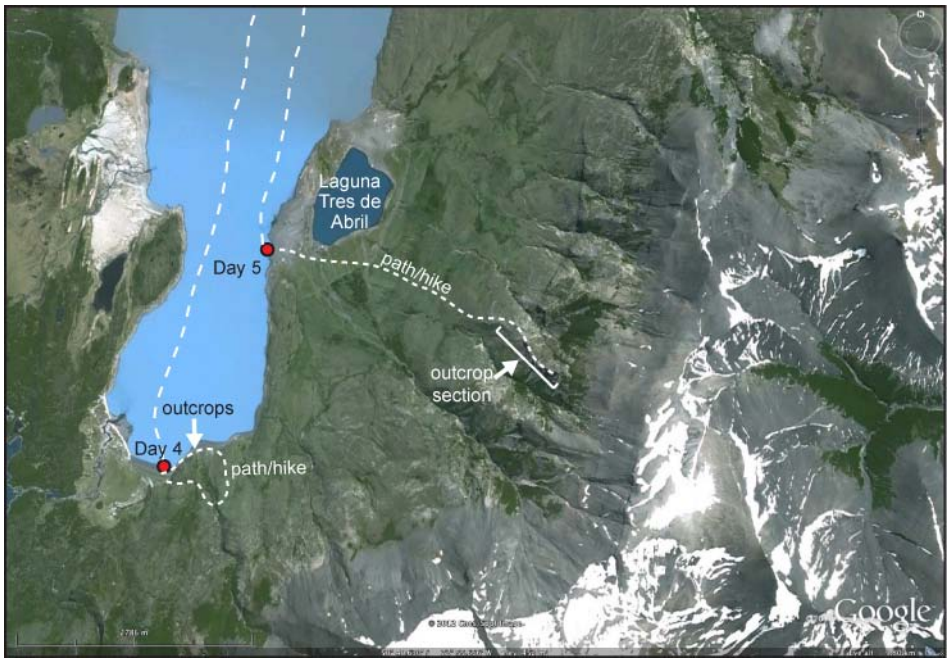


Figure 4.2. GoogleEarth satellite view showing the detailed outcrop locations for days 4 and 5.

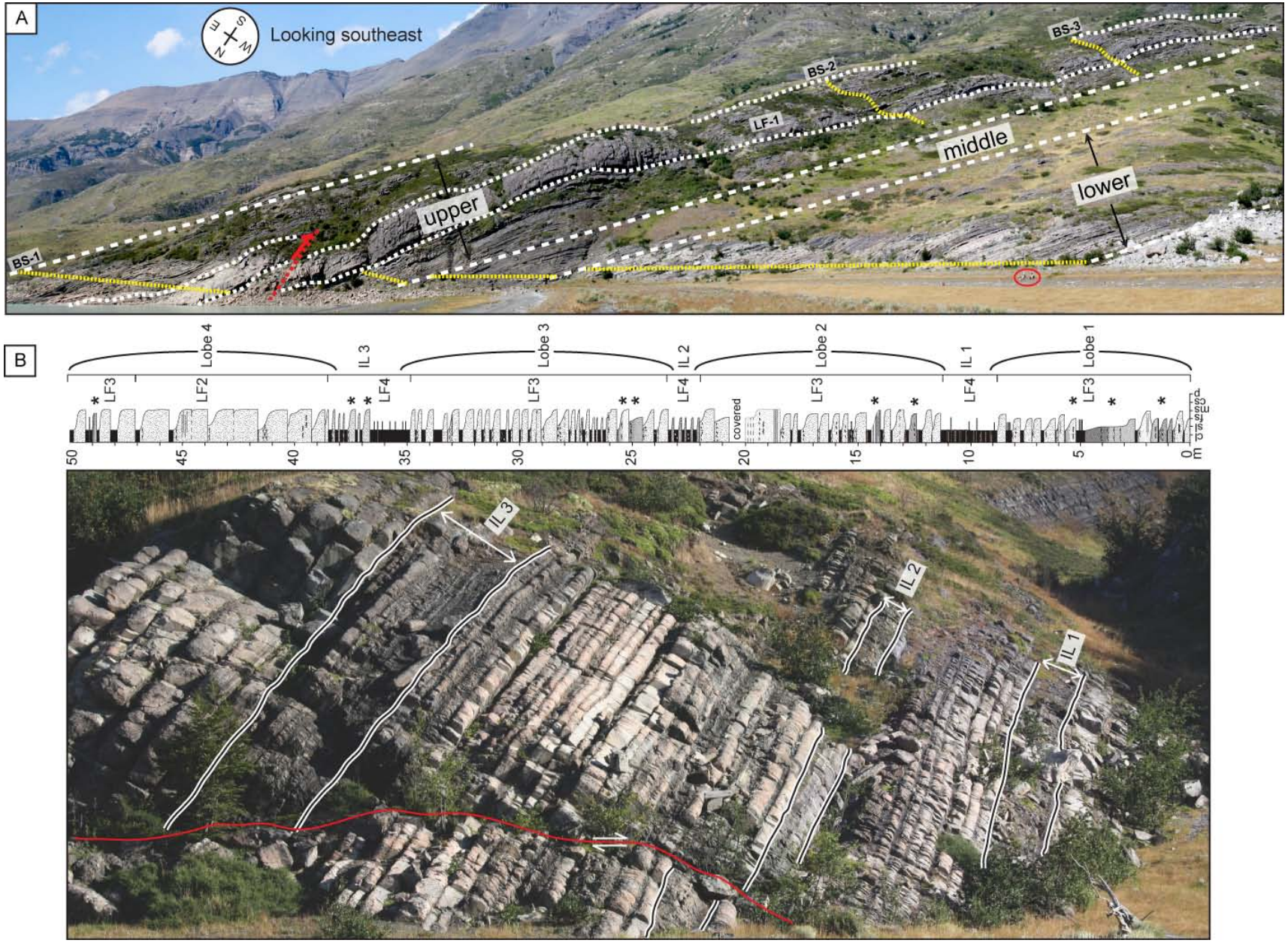

A
Looking southeast
BS-1
BS-2
BS-3
LF-1
upper
middle
lower
B
Lobe 4
Lobe 3
Lobe 2
Lobe 1
IL 3
IL 2
IL 1
LF3
LF2
LF4
covered
50
45
40
35
30
25
20
15
10
5
0
m

Figure 4.3. (previous page) (A) Photopan showing nearly the entire outcrop at Brazo Sur. Yellow dotted lines denote the approximate routes where sections were measured (people circled for scale). (B) Example photo and measured section from the lower 50 meters of the BS section showing how the outcrop expression corresponds to the classification of lobe and inter-lobe (IL) or lobe margin deposits. Red line represents the approximate trace of a small (~3 m of offset) localized fault (Malkowski et al., in review).

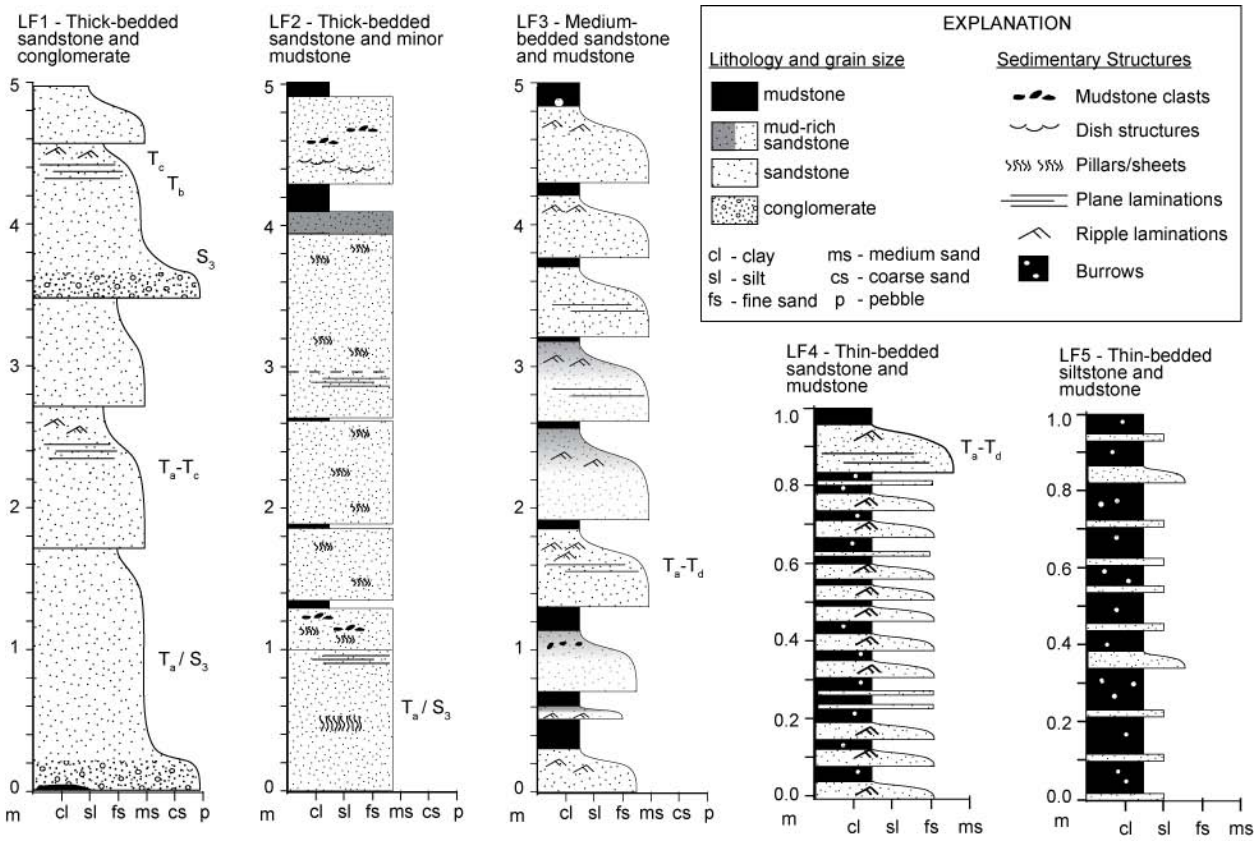


Figure 4.4. Examples of the 5 lithofacies identified in outcrop. (From Malkowski et al., in review)

Notes:

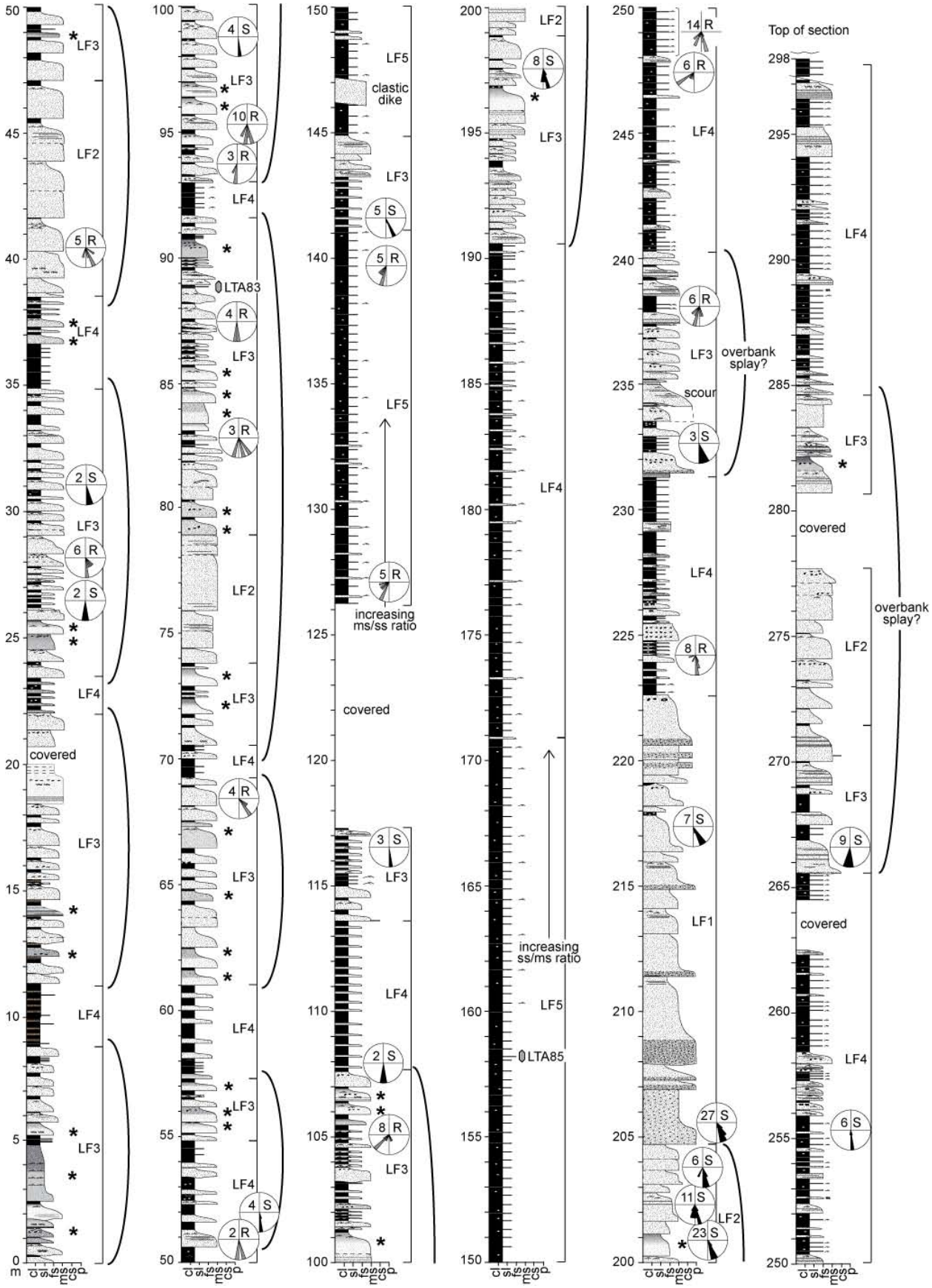


Figure 4.5. Measured stratigraphic section from Brazo Sur. See Figure 4.6 for legend.

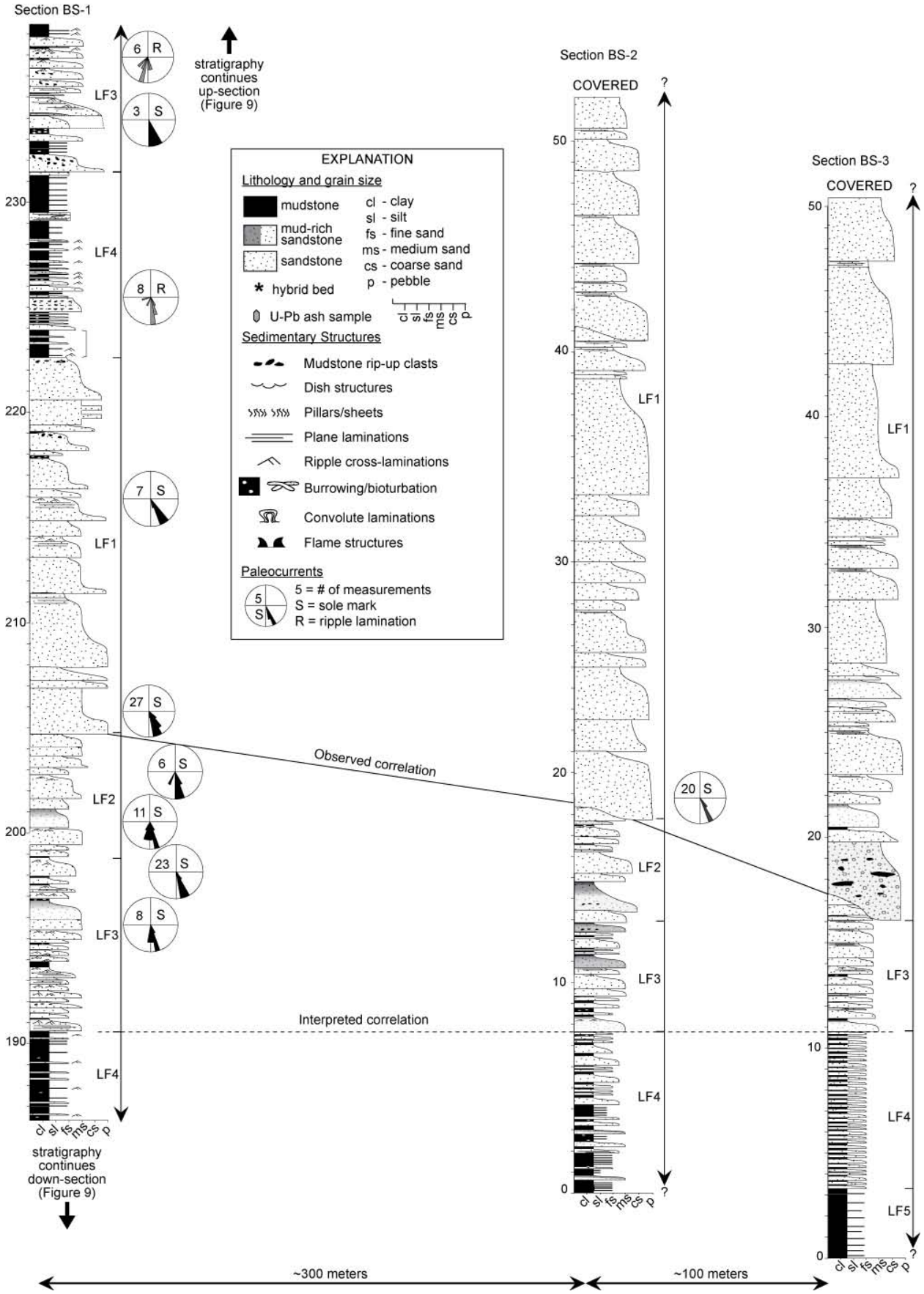

Section BS-1
stratigraphy continues up-section (Figure 9)
stratigraphy continues down-section (Figure 9)
EXPLANATION
Lithology and grain size
mudstone
mud-rich sandstone
sandstone
hybrid bed
U-Pb ash sample
cl - clay
sl - silt
fs - fine sand
ms - medium sand
cs - coarse sand
p - pebble
Sedimentary Structures
Mudstone rip-up clasts
Dish structures
Pillars/sheets
Plane laminations
Ripple cross-laminations
Burrowing/bioturbation
Convolute laminations
Flame structures
Paleocurrents
5 = # of measurements
S = sole mark
R = ripple lamination
LF1
LF2
LF3
LF4
Observed correlation
Interpreted correlation
Section BS-2
COVERED
Section BS-3
COVERED
~300 meters
~100 meters

Figure 4.6. (previous page) Lateral correlation of LF-1 units from sections measured at Brazo Sur. Note the lateral thickness variations (~18 – 34 m) in LF-1. See Figure 5 for section locations on outcrop.

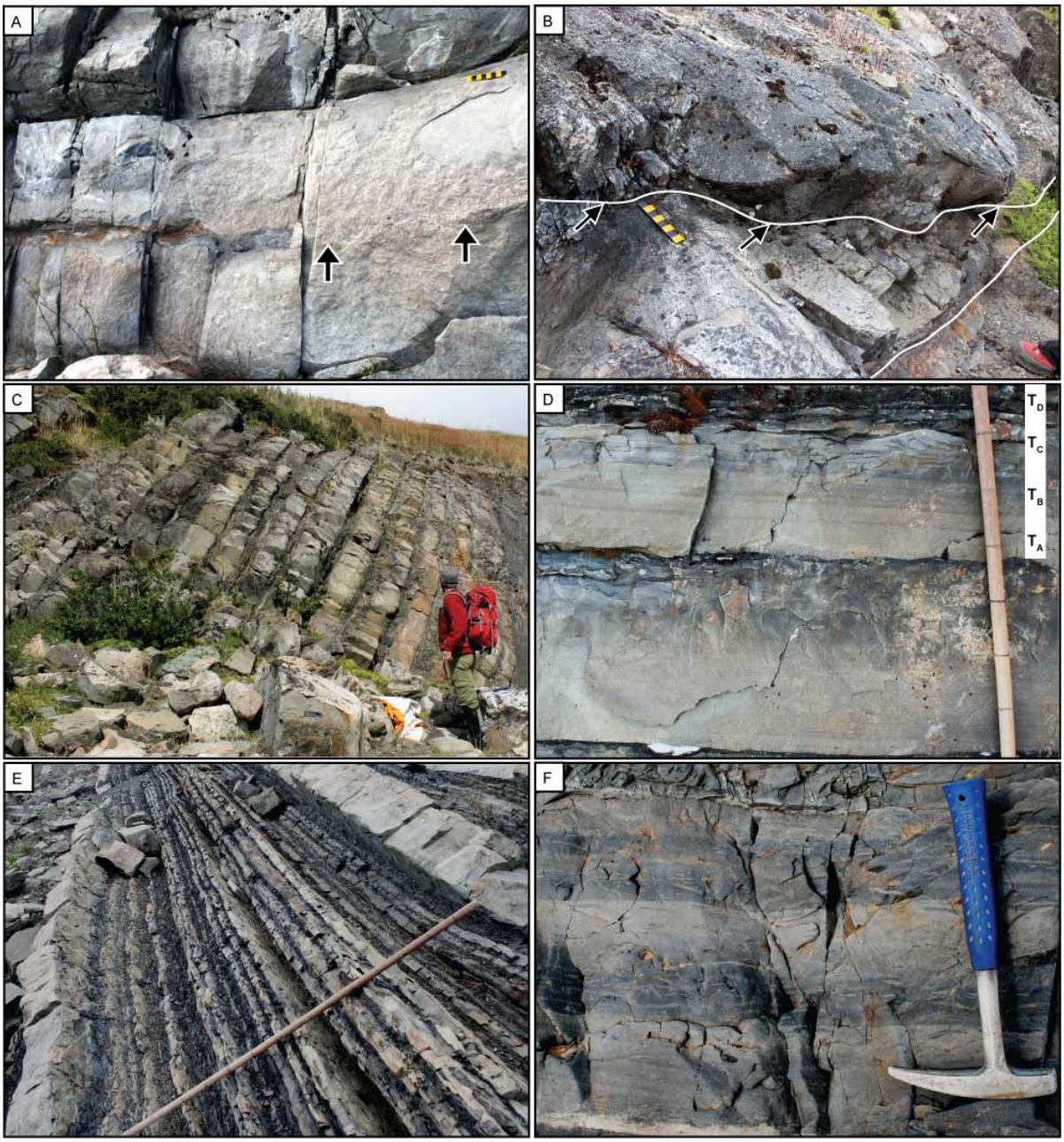


Figure 4.7. Examples of bedding style and sedimentological character. A) Lenticular beds showing basal scour and amalgamation that is common in LF1. Scale is 16 centimeters. B) Localized scouring (down-stepping toward the southwest) of LF1 in the BS-2 section. Scale is 16 centimeters. C) Example of tabular units of interbedded sandstone and mudstone (LF3). D) Upper bed shows preservation of Ta-Td Bouma divisions. Scale in 10 centimeter increments. E) Repeated beds of thin, low-density turbidites characteristic of LF4. Scale in 10 centimeter increments. F) Bioturbated siltstone and mudstone beds (LF5).

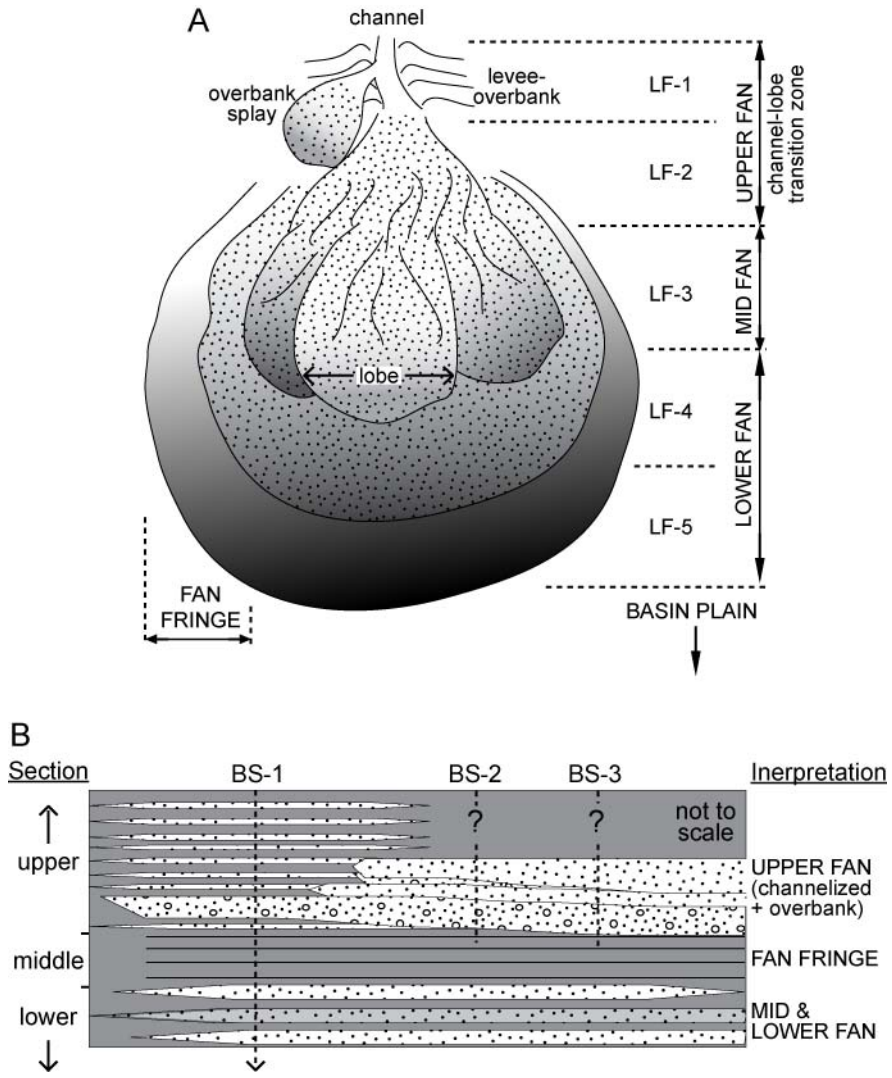


Figure 4.8. A) Depositional setting diagram and nomenclature for submarine fan systems. Modified from Howell and Normark (1982) and references within. B) Schematic cross-sectional interpretations of the Brazo Sur sections showing the overall progradational architecture from mid-lower fan to upper fan (Malkowski et al., in review)

Notes:

DAY 5 – Friday, 6 March 2015

Destination: Cerro Toro Formation on Brazo Sur de Lago Argentino

Today will consist of a boat ride from Estancia Nibepo Aike, near Lago Roca, to the southeastern end of the Brazo Sur de Lago Argentino. On the outcrop, we will use the day to investigate outcrops of canyon (?) and mass-wasting deposits of the Cerro Toro Formation. Departure times are TBD.

Driving Directions: Hotel Mirador del Lago to Estancia Nibepo Aike (approx. 2 hours driving time)

1. Head **west** on **Av del Libertador San Martin** toward **Calle 91** ..... 54 m
2. Take **first left** onto **Calle 91** ..... 12 m
3. Take **first left** onto **Av del Libertador San Martin** ..... 120 m
4. Take **first right** onto **Napoleon Irusta** ..... 250 m
5. Turn **left** onto **Av Juan Domingo Peron** ..... 230 m
6. Turn **right** onto **Comodoro Luis Piedrabuena** ..... 450 m
7. Turn **right** onto **Av 17 de Octubre** .....1.7 km
8. Continue onto **RP15**.....50.4 km
9. Park in designated Estancia Nibepo Aike parking lot.

Accommodations (6 March): Hotel Mirador del Lago, El Calafate.

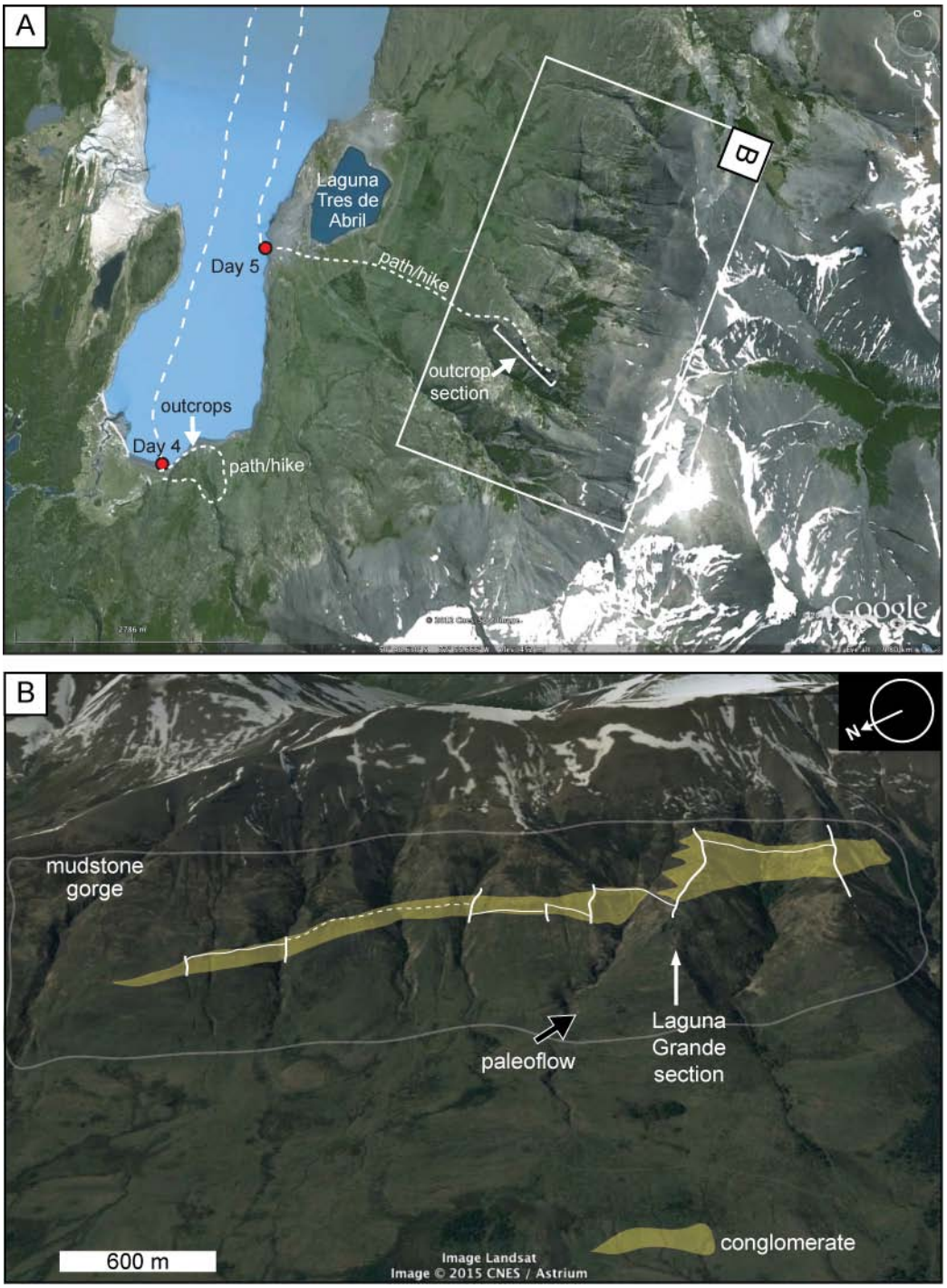


Figure 5.1. GoogleEarth satellite imagery of the Brazo Sur region and Laguna Tres de Abril. (A) Image showing the general path and location to the "Laguna Grande" outcrop section. (B) Image looking east at the outcrop face highlighting the general upward trend of mapped conglomerate units from north to south.

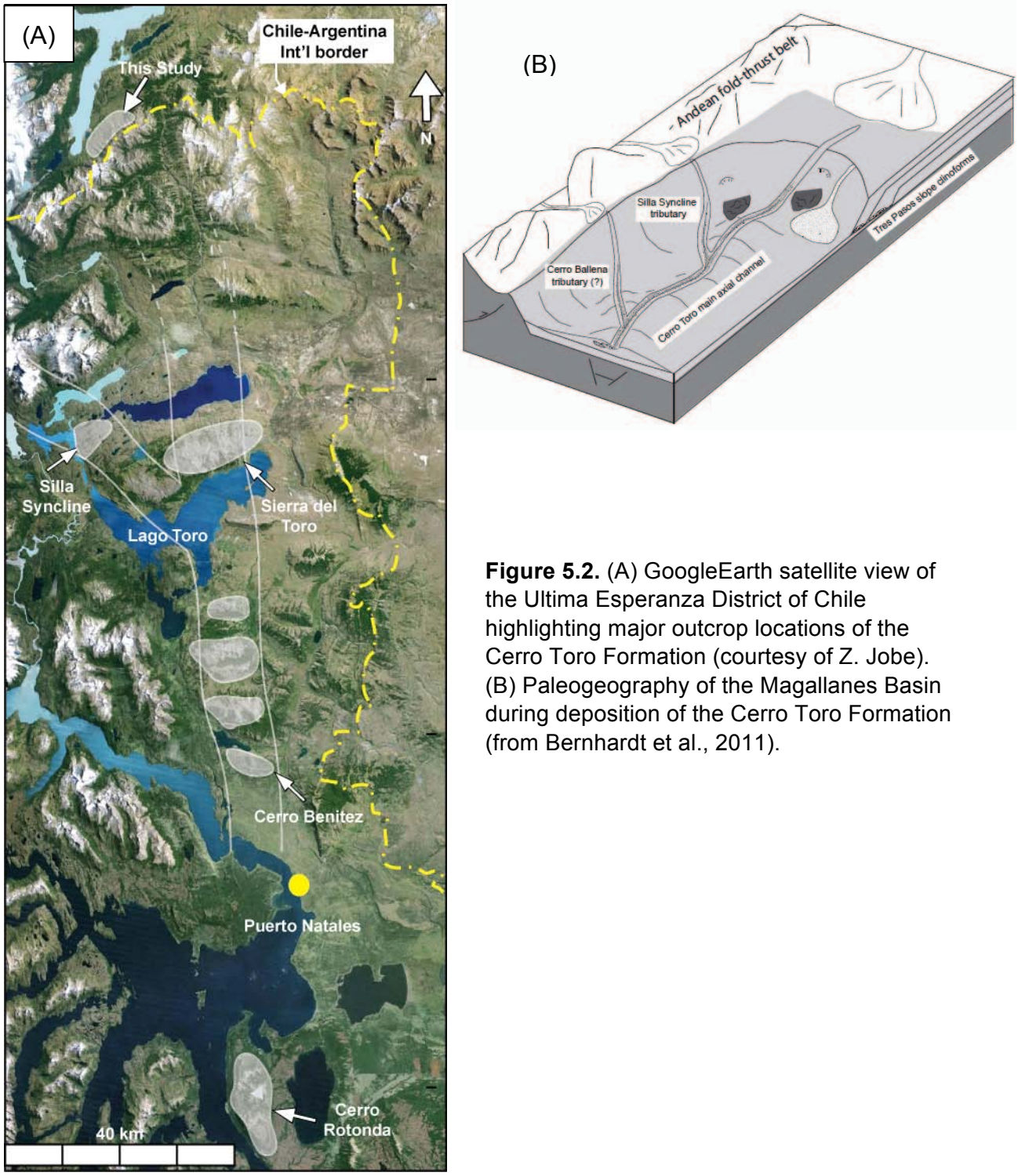


Figure 5.2. (A) GoogleEarth satellite view of the Ultima Esperanza District of Chile highlighting major outcrop locations of the Cerro Toro Formation (courtesy of Z. Jobe). (B) Paleogeography of the Magallanes Basin during deposition of the Cerro Toro Formation (from Bernhardt et al., 2011).

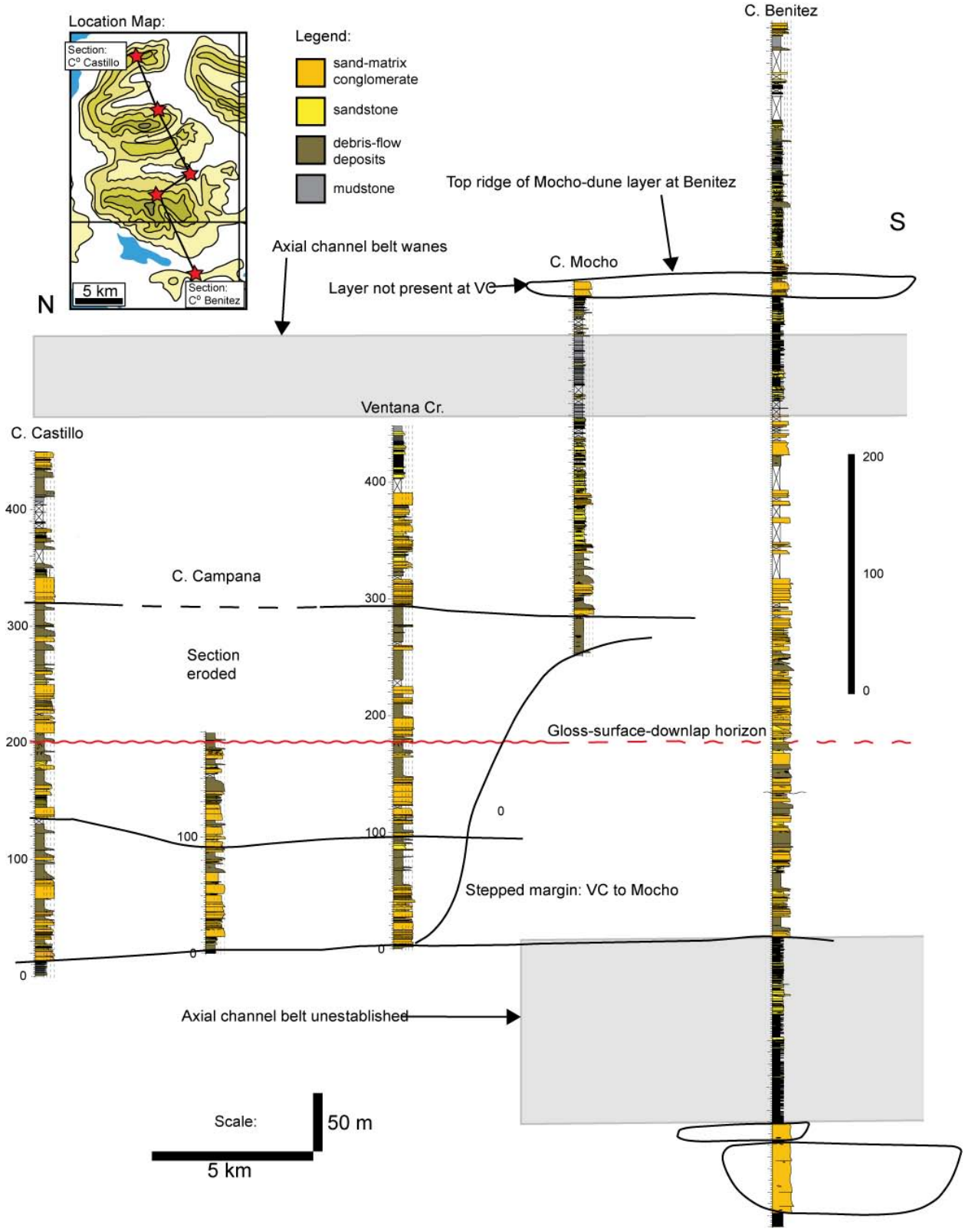


Figure 5.3. Regional architecture of the Cerro Toro Formation in the Ultima Esperanza District of Chile from Cerro Castillo south to Cerro Benitez (from Hubbard, 2006; Hubbard et al., 2008)

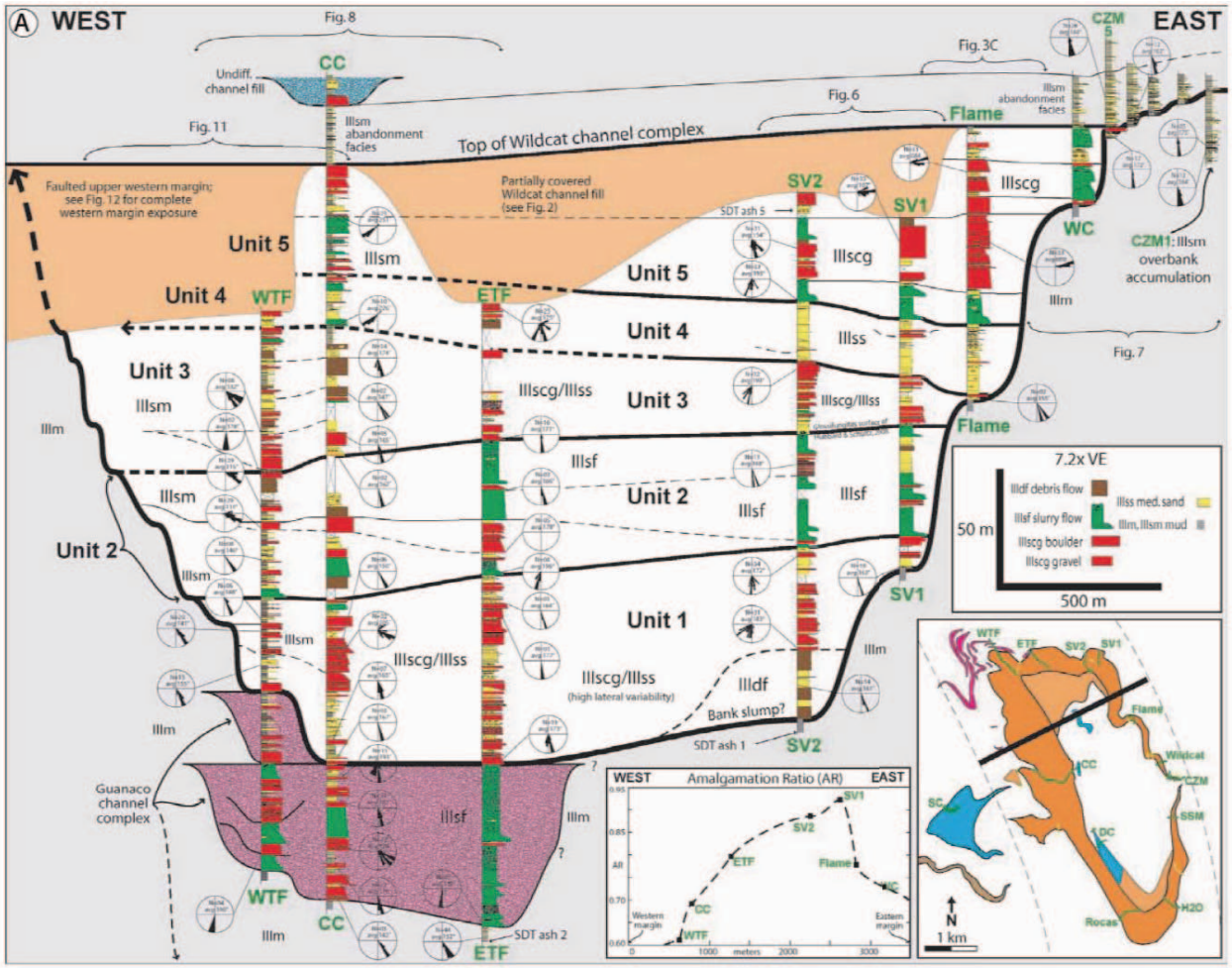


Figure 5.4. (from Jobe et al., 2010) Facies and architecture of the Cerro Toro Formation olong Sierra del Toro in the Ultima Esperaza District, Chile.

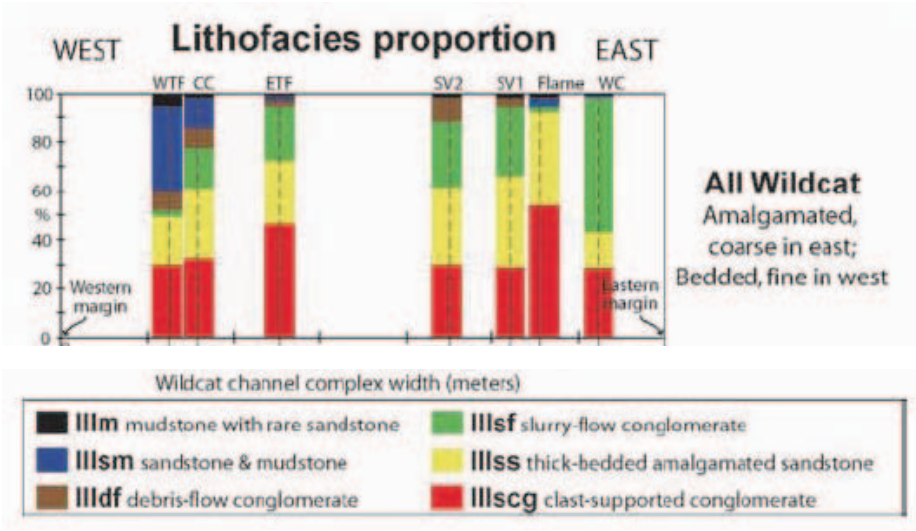


Figure 5.5. (from Jobe et al., 2010) Combined lithofacies proportions of the Wildcat channel complex from the Cerro Toro Formation along Sierra del Toro.

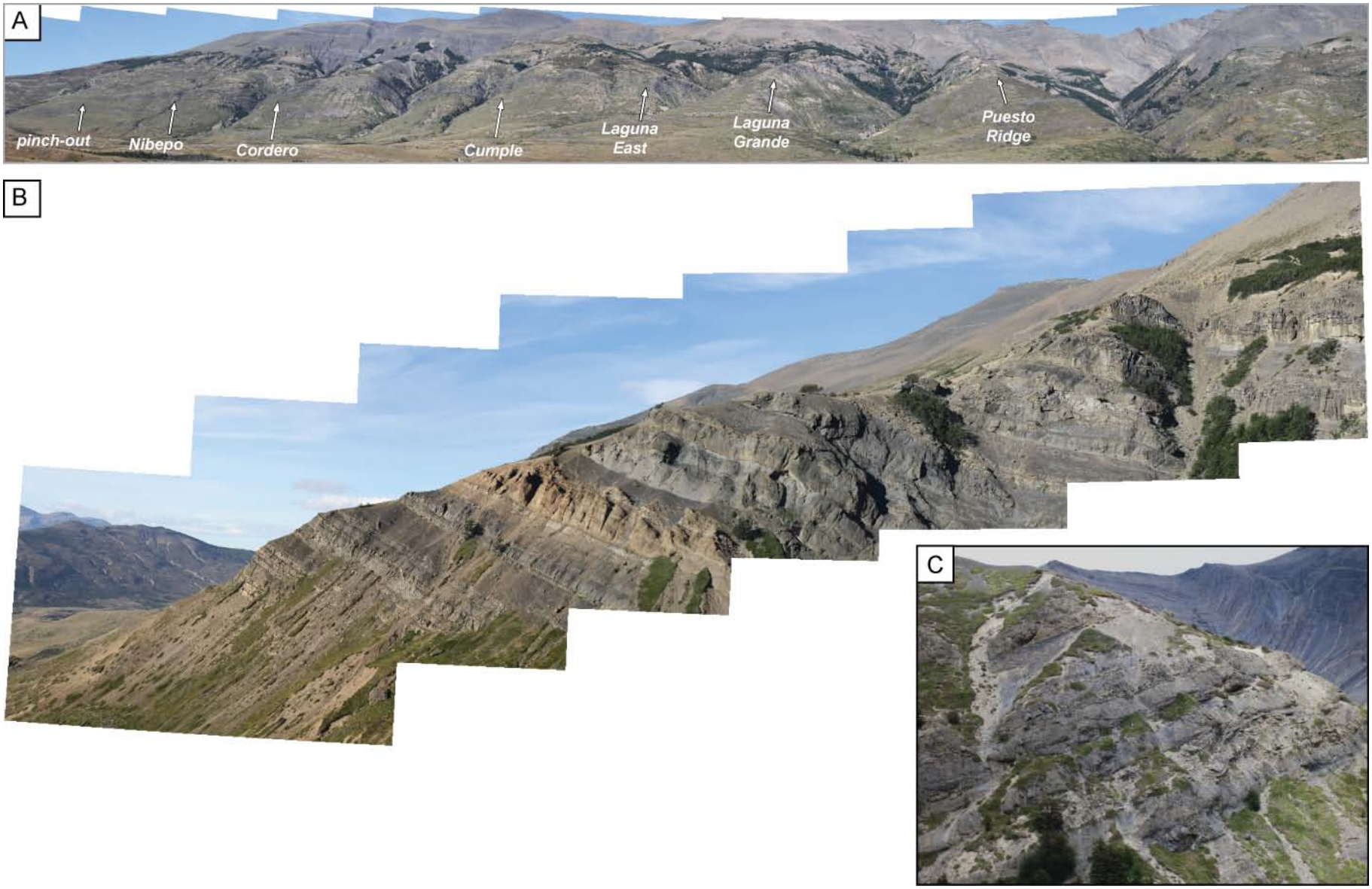


Figure 5.6. (A) Photopan looking east at the roughly north-south trending outcrop belt of the Cerro Toro Formation. (B) Photopan (looking ~north) of the stratigraphy that makes up the "Laguna Grande" section. (C) Photo (looking ~south) of the stratigraphy along "Puesto Ridge".

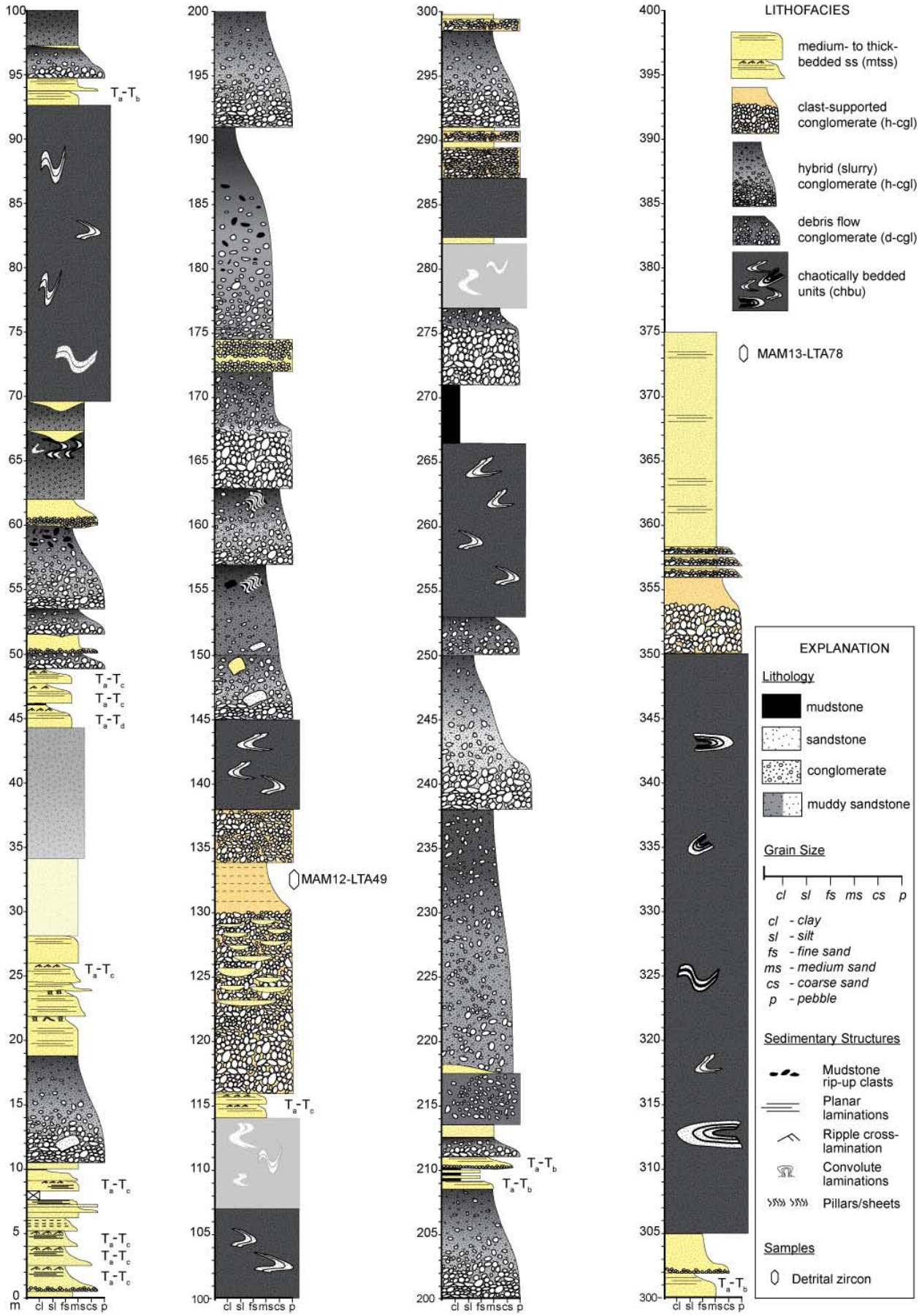

LITHOFACIES
medium- to thick-bedded ss (mtss)
clast-supported conglomerate (h-cgl)
hybrid (slurry) conglomerate (h-cgl)
debris flow conglomerate (d-cgl)
chaotically bedded units (chbu)
MAM13-LTA78
MAM12-LTA49
EXPLANATION
Lithology
mudstone
sandstone
conglomerate
muddy sandstone
Grain Size
cl sl fs ms cs p
cl - clay
sl - silt
fs - fine sand
ms - medium sand
cs - coarse sand
p - pebble
Sedimentary Structures
Mudstone rip-up clasts
Planar laminations
Ripple cross-lamination
Convolute laminations
Pillars/sheets
Samples
Detrital zircon
m
cl sl fs ms cs p

Figure 5.7. (previous page) Measured stratigraphy of the “Laguna Grande” section.

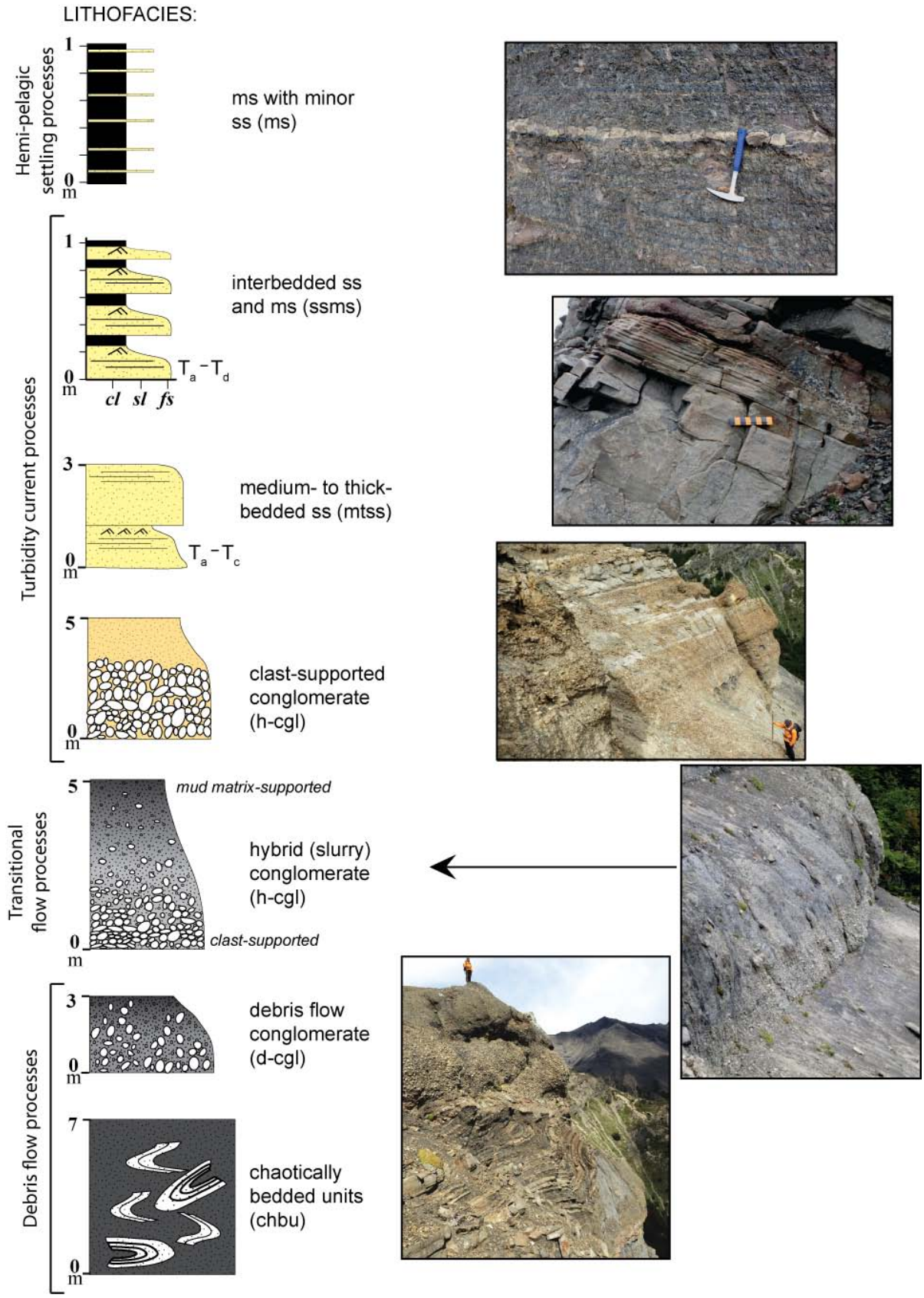


Figure 5.8. Lithofacies of the Cerro Toro Formation near Laguna Tres de Abril

ALTERNATE OPTION #1

Destination: Cerro Toro Formation and/or Alta Vista Fm at Cerro Cristales

Today will consist of a day hike in the Parque Nacional de los Glaciares, up Cerro Cristales. On the outcrop, we will use the day to investigate deformed outcrops of slope (?) facies including MTDs. We will depart from Hotel Mirador del Lago at 8:00 am. <u>This hike is not advised if there is bad weather.</u>

Driving Directions: Hotel Mirador del Lago to Cerro Cristales trail head (Parque Nacional de los Glaciares) (approx. 1 hour, 45 minutes driving time)

1. Head **west** on **Av del Libertador San Martin** toward **Calle 91** ..... 54 m
2. Take **first left** onto **Calle 91** ..... 12 m
3. Take **first left** onto **Av del Libertador San Martin** ..... 120 m
4. Take **first right** onto **Napoleon Irusta** ..... 250 m
5. Turn **left** onto **Av Juan Domingo Peron** ..... 230 m
6. Turn **right** onto **Comodoro Luis Piedrabuena** ..... 450 m
7. Turn **right** onto **Av 17 de Octubre** .....1.7 km
8. Continue onto **RP15**.....~45 km
9. Park along road.

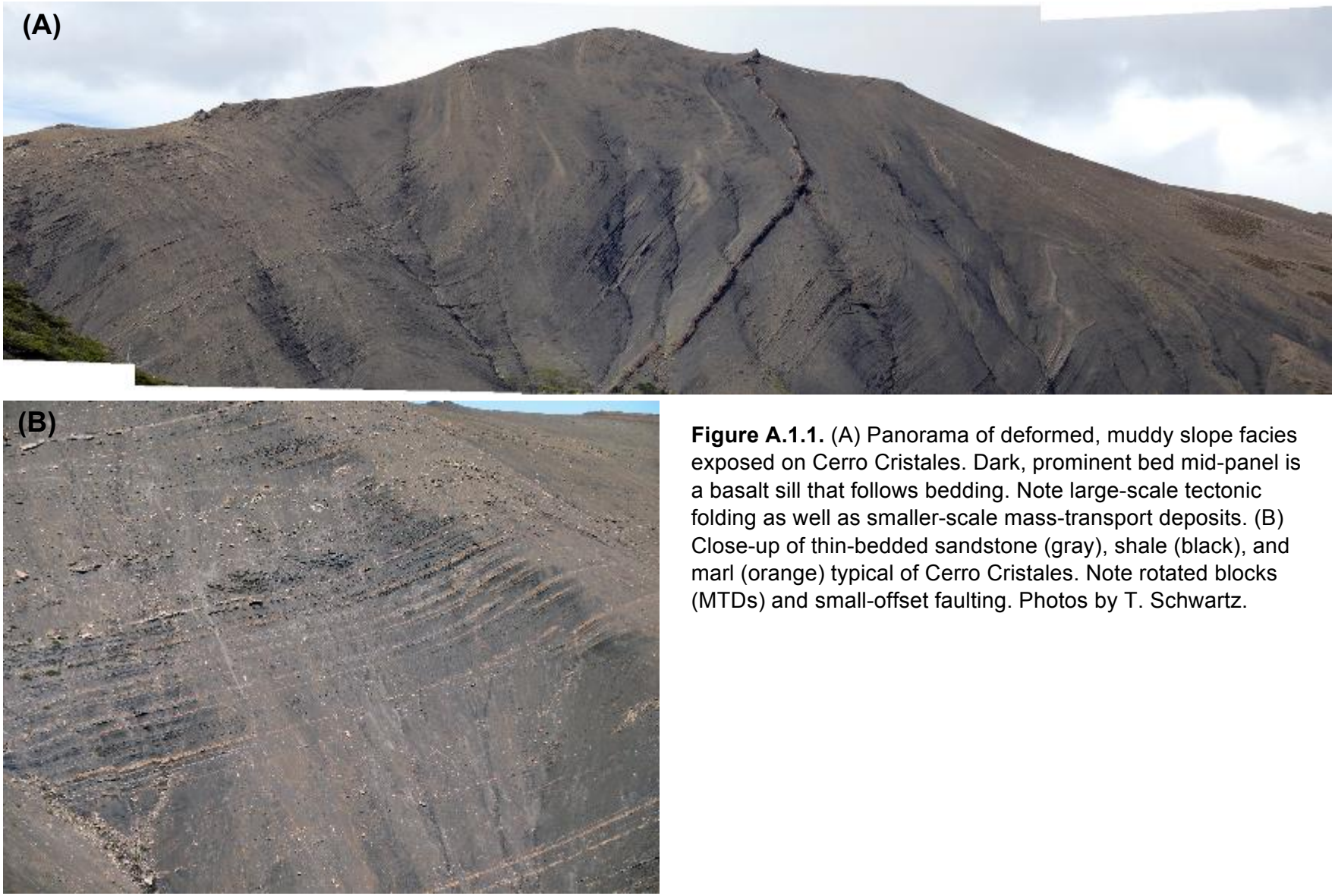


Figure A.1.1. (A) Panorama of deformed, muddy slope facies exposed on Cerro Cristales. Dark, prominent bed mid-panel is a basalt sill that follows bedding. Note large-scale tectonic folding as well as smaller-scale mass-transport deposits. (B) Close-up of thin-bedded sandstone (gray), shale (black), and marl (orange) typical of Cerro Cristales. Note rotated blocks (MTDs) and small-offset faulting. Photos by T. Schwartz.

Notes:

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