Miocene Tectonic and Stratigraphic Evolution of the Central Baja California Peninsula and Rapid Marine Flooding Into the Gulf of California at ca. 6.3 Ma

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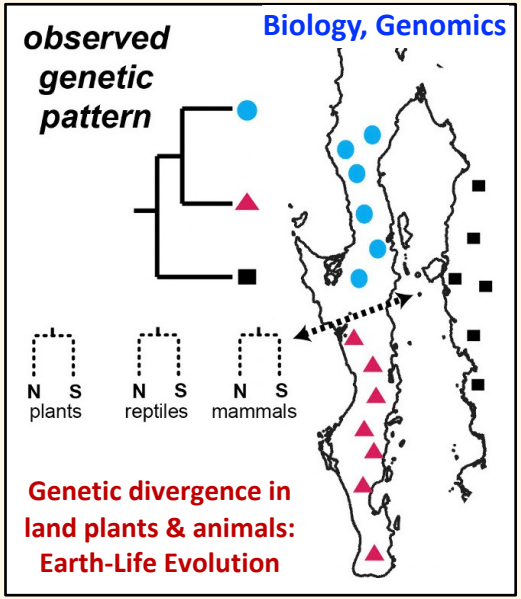
Darin, M.H., Bennett, S.E.K., Hausback, B.P., Gardner, K.K., Niemi, T.M., Busby, C., Graettinger, A., Salgado Muñoz, V.O., Martinez Gutierrez, G., Morebeck, C., Usher, E., Heizler, M.T., Pecha, M.E., Stelten, M., Schmitt, A., Dolby, G.A.

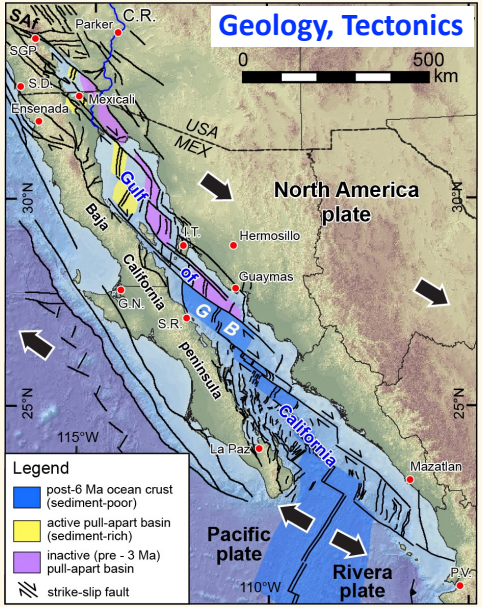
Two Collaborative Projects

Baja Geogenomics (BGG)

Baja GeoGenomics Consortium

Baja Basins (2017 – 2022)



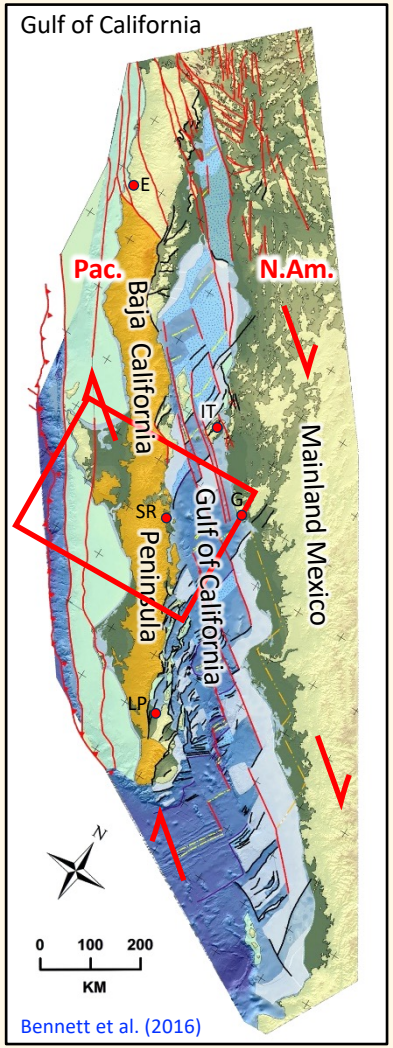


Tectonic Setting

- Gulf of California: opens by relative plate motion across oblique **transform-rift Pac-NAM** plate boundary (long transform faults).
- Baja California Microplate moves NW relative to North America at modern rate (gps): ~45 mm/yr (Plattner et al., 2015, JGR).

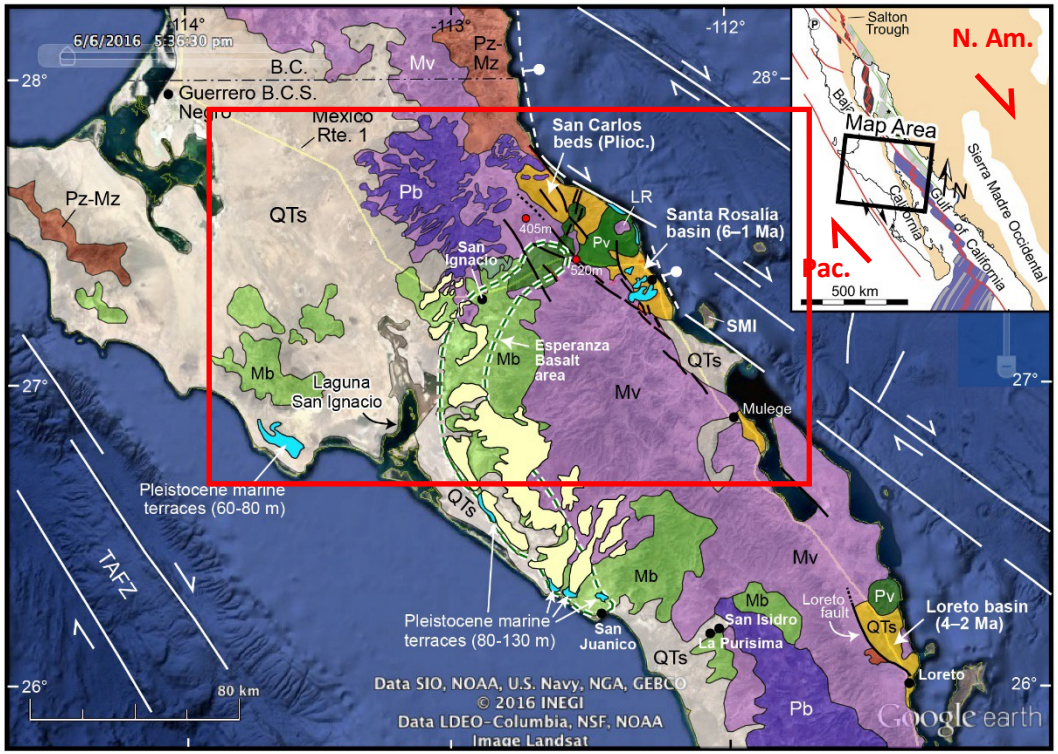
Late Cenozoic Tectonic History of Central Baja Peninsula

1) 30 – 12 Ma: Farallon plate subduction & arc magmatism
2) 12 – 8 Ma: End of subduction, reorganization, oblique extension
3) ~ 8 – 0 Ma: Strike-slip motion on plate boundary (in Gulf of Cal.)
   - **Santa Rosalía Basin** - transtensional pull-apart basin
   - Stratigraphic record of rapid **marine flooding at ~ 6.3 Ma …**
   - During onset of seafloor spreading in Guaymas basin:
   - **Geologically instantaneous** regional marine inundation.



Bennett et al. (2016)

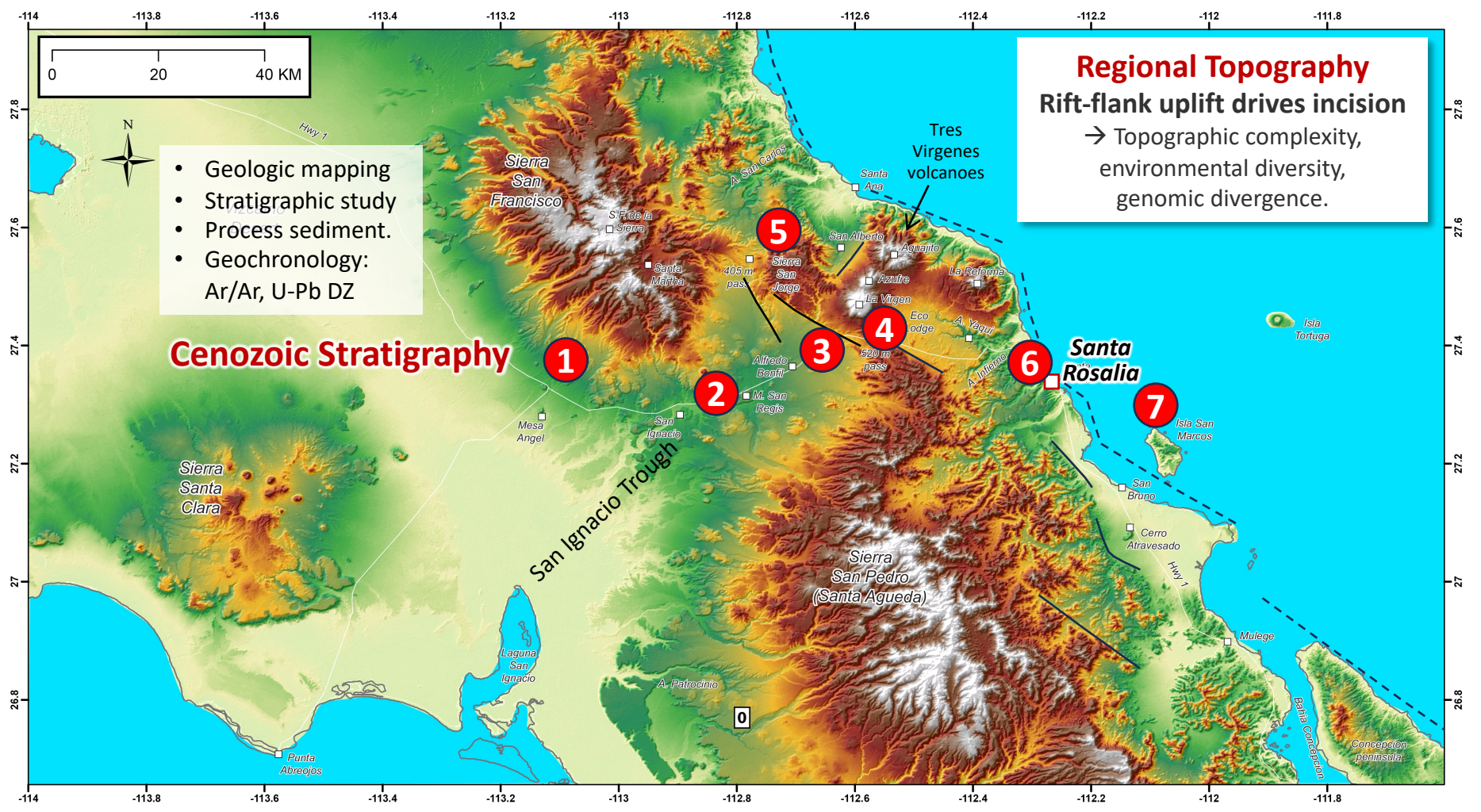
Geology of the Central Baja California Peninsula

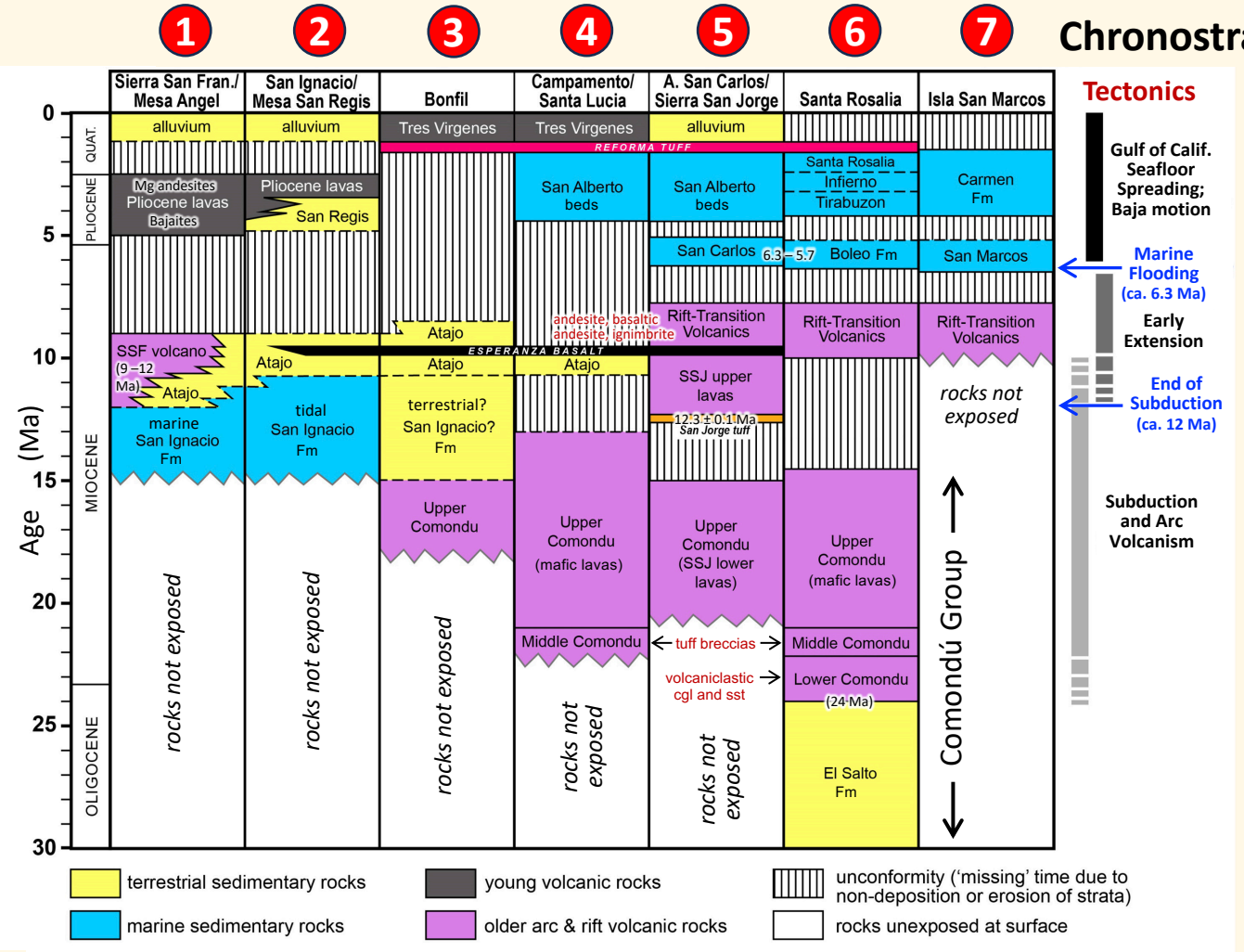


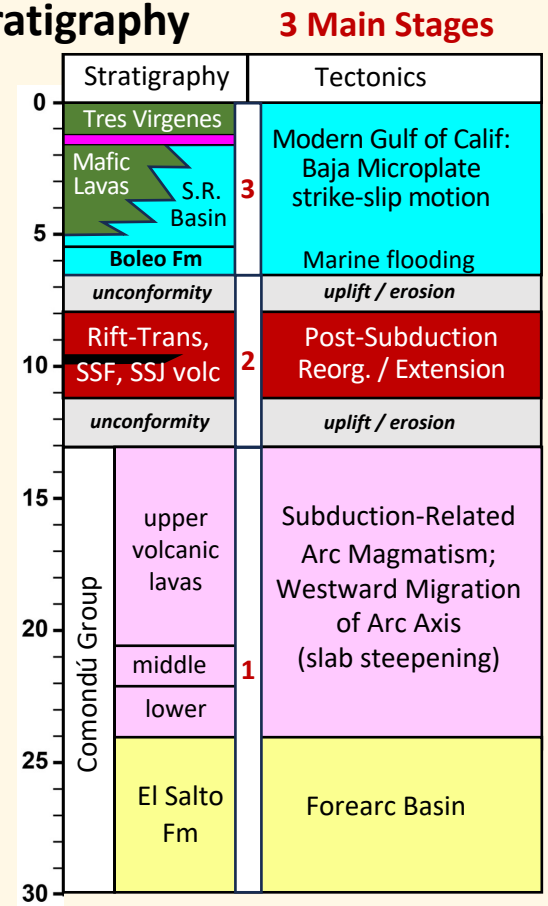
- Miocene subduction-related volcanic/volcaniclastic rocks.
- Plio-Pleis. volc & sed deposits
- Belt of strike-slip & normal faults and fault-bounded basins in NE.

Santa Rosalía Basin

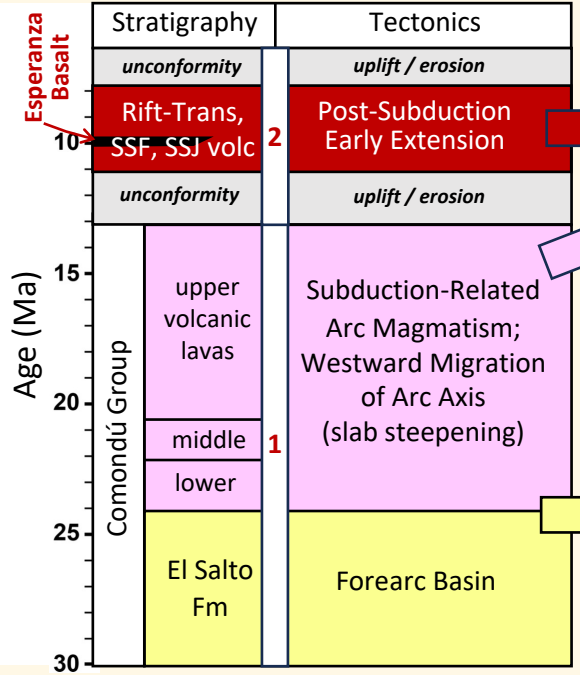
- 80-km long, late Mioc. to Pleist. sedimentary rocks.
- Records opening of the Gulf of California transform-rift.
- Initiated ~ 6.3 Ma (this study).
- Inverted/uplifted by La Reforma volcano starting ~ 1.4 Ma.

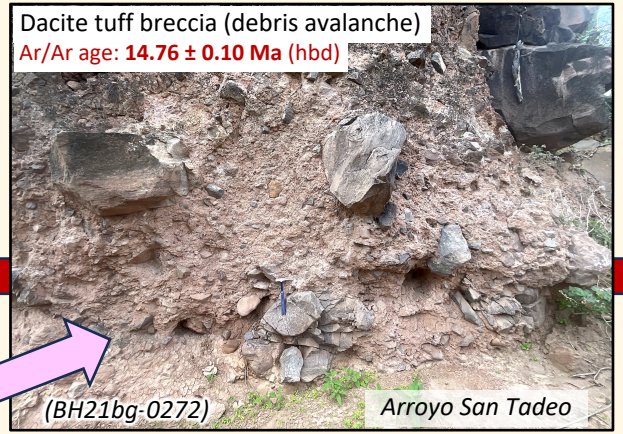

Regional Topography
Rift-flank uplift drives incision
→ Topographic complexity, environmental diversity, genomic divergence.
Tres Virgenes volcanoes
Cenozoic Stratigraphy
• Geologic mapping
• Stratigraphic study
• Process sediment.
• Geochronology: Ar/Ar, U-Pb DZ
0 20 40 KM
N
Sierra San Francisco
Sierra Santa Clara
Sierra San Pedro (Santa Agueda)
Sierra San Jorge
San Ignacio Trough
Santa Rosalia
Isla Tortuga
Isla San Marcos
Laguna San Ignacio
Punta Abreojos
Mesa Angel
San Ignacio
M. San Regis
Alfredo Bonfil
Santa Martha
S. F. de la Sierra
Santa Ana
San Alberto
Aquajito
Azufre
La Virgen
La Reforma
Eco Lodge
A. Yecui
A. Infierno
405 m pass
520 m pass
A. San Carlos
A. Patrocinio
San Bruno
Cerro Atravesado
Mulege
Bahia Concepcion
Concepcion peninsula
Hwy 1
1
2
3
4
5
6
7

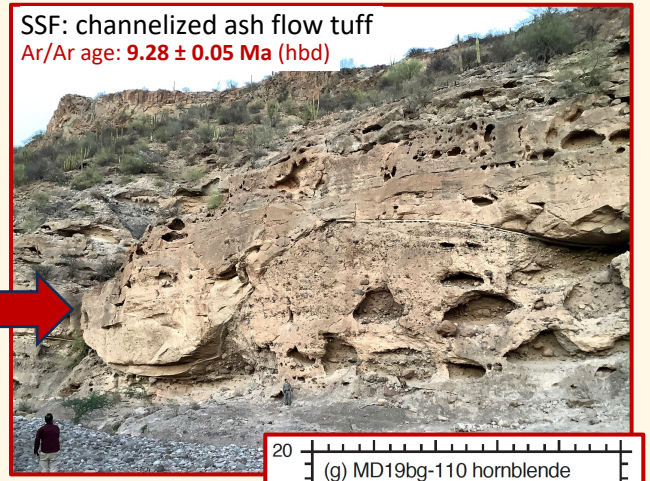

1
2
3
4
5
6
7
Chronostratigraphy
Sierra San Fran./ Mesa Angel
San Ignacio/ Mesa San Regis
Bonfil
Campamento/ Santa Lucia
A. San Carlos/ Sierra San Jorge
Santa Rosalia
Isla San Marcos
Age (Ma)
QUAT.
PLIOCENE
MIOCENE
OLIGOCENE
alluvium
Mg andesites
Pliocene lavas
Bajaites
Pliocene lavas
San Regis
Tres Virgenes
REFORMA TUFF
San Alberto beds
Santa Rosalia
Infierno
Tirabuzon
Carmen Fm
San Carlos
6.3 – 5.7
Boleo Fm
San Marcos
Atajo
andesite, basaltic andesite, ignimbrite
Rift-Transition Volcanics
SSF volcano (9 –12 Ma)
ESPERANZA BASALT
SSJ upper lavas
12.3 ± 0.1 Ma
San Jorge tuff
marine San Ignacio Fm
tidal San Ignacio Fm
terrestrial? San Ignacio? Fm
Upper Comondu
Upper Comondu (mafic lavas)
Upper Comondu (SSJ lower lavas)
rocks not exposed
Middle Comondu
tuff breccias
volcaniclastic cgl and sst
Lower Comondu
(24 Ma)
El Salto Fm
Comondú Group
Tectonics
Gulf of Calif. Seafloor Spreading; Baja motion
Marine Flooding (ca. 6.3 Ma)
Early Extension
End of Subduction (ca. 12 Ma)
Subduction and Arc Volcanism
terrestrial sedimentary rocks
marine sedimentary rocks
young volcanic rocks
older arc & rift volcanic rocks
unconformity ('missing' time due to non-deposition or erosion of strata)
rocks unexposed at surface

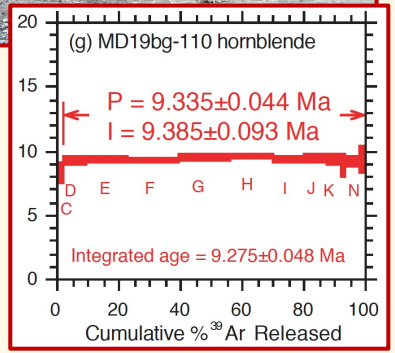

3 Main Stages
Stratigraphy
Tectonics
Tres Virgenes
Mafic Lavas
S.R. Basin
Boleo Fm
unconformity
Rift-Trans, SSF, SSJ volc
unconformity
Comondú Group
upper volcanic lavas
middle
lower
El Salto Fm
3
2
1
Modern Gulf of Calif: Baja Microplate strike-slip motion
Marine flooding
uplift / erosion
Post-Subduction Reorg. / Extension
uplift / erosion
Subduction-Related Arc Magmatism; Westward Migration of Arc Axis (slab steepening)
Forearc Basin

Stages 1 and 2: Tectonic-Magmatic Evolution (Highlights)

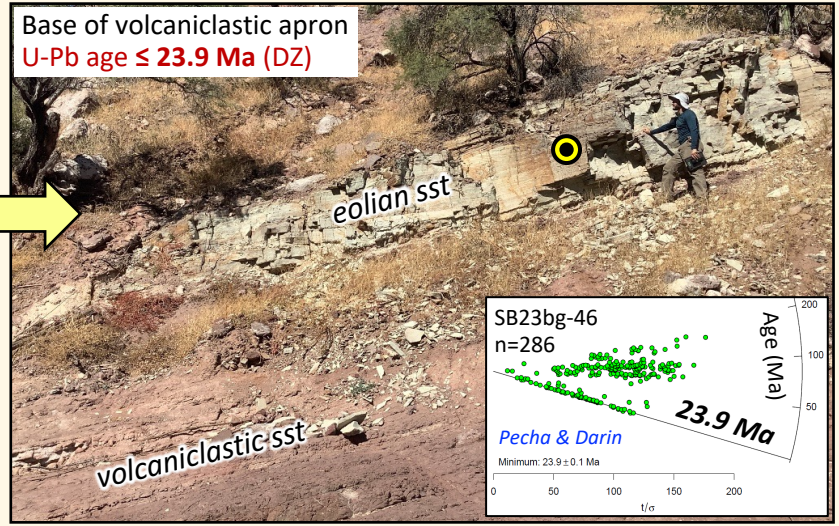






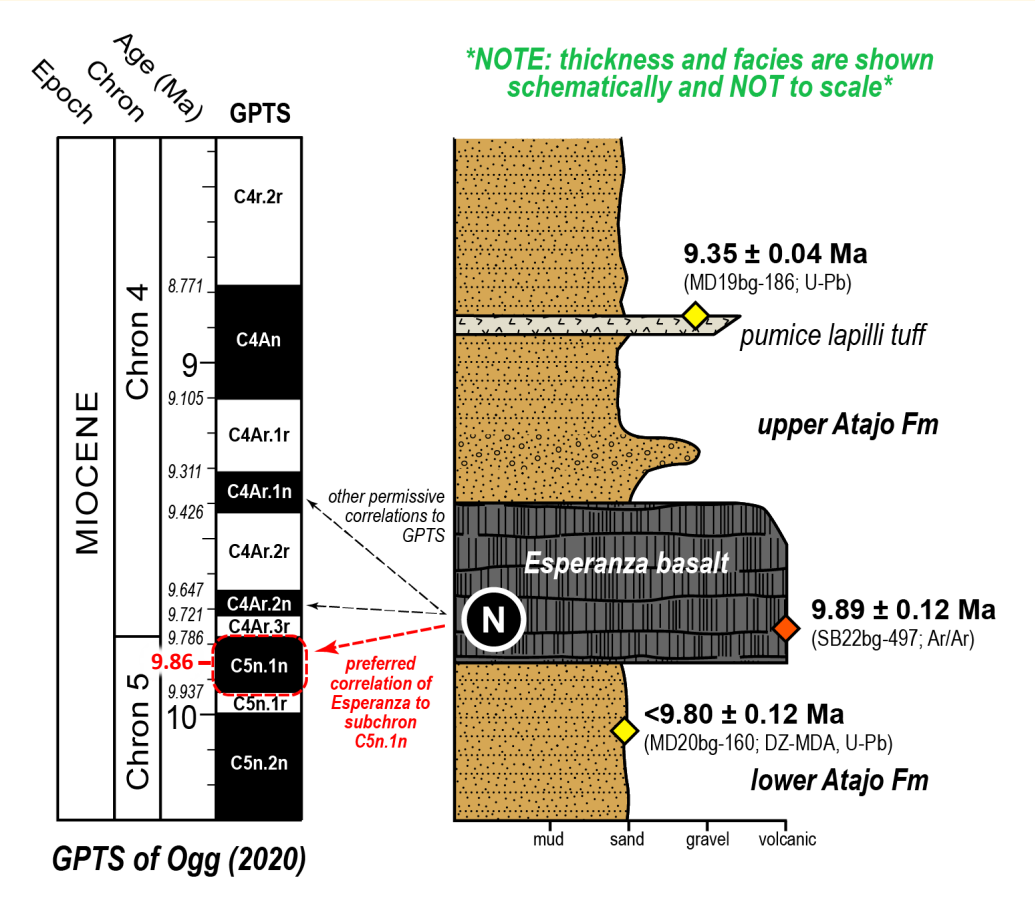


M. Heizler

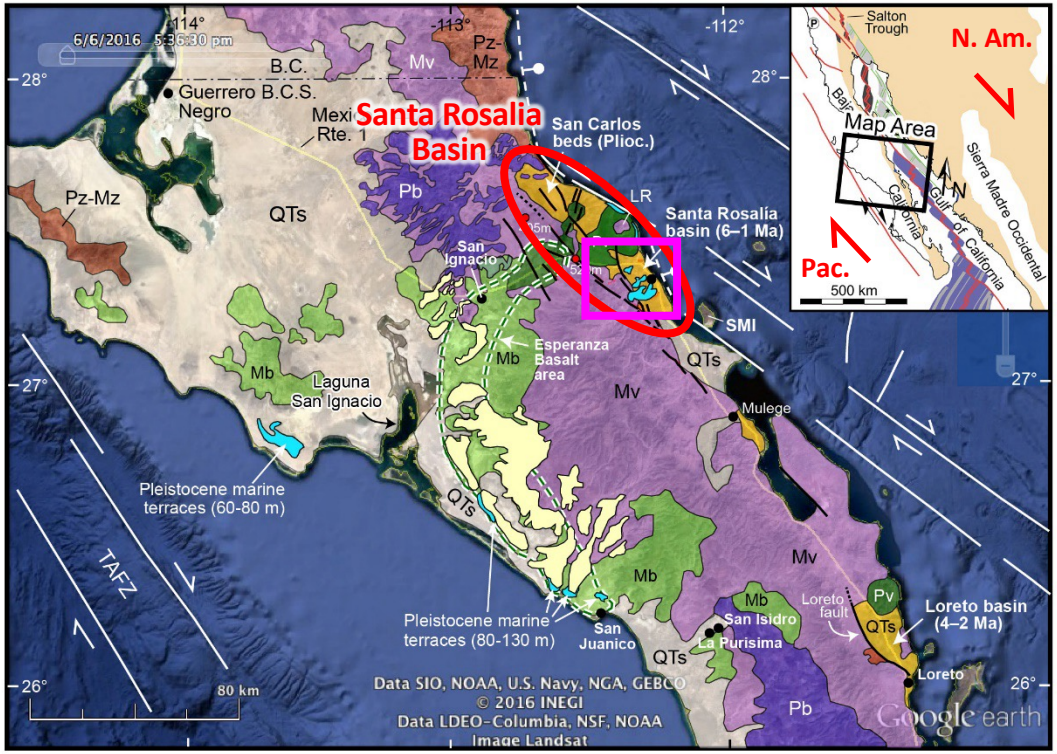


Esperanza Basalt

- Regionally extensive tholeiitic basalt, thin flows, early post-subduction.
- Previously published ages: 7.6 – 12.5 Ma.
- New paleomag and age data (this study): Esperanza has **normal** polarity.
- **Basalt emplaced ca. 9.9 Ma**



(3) Initiation of the Central Gulf of California



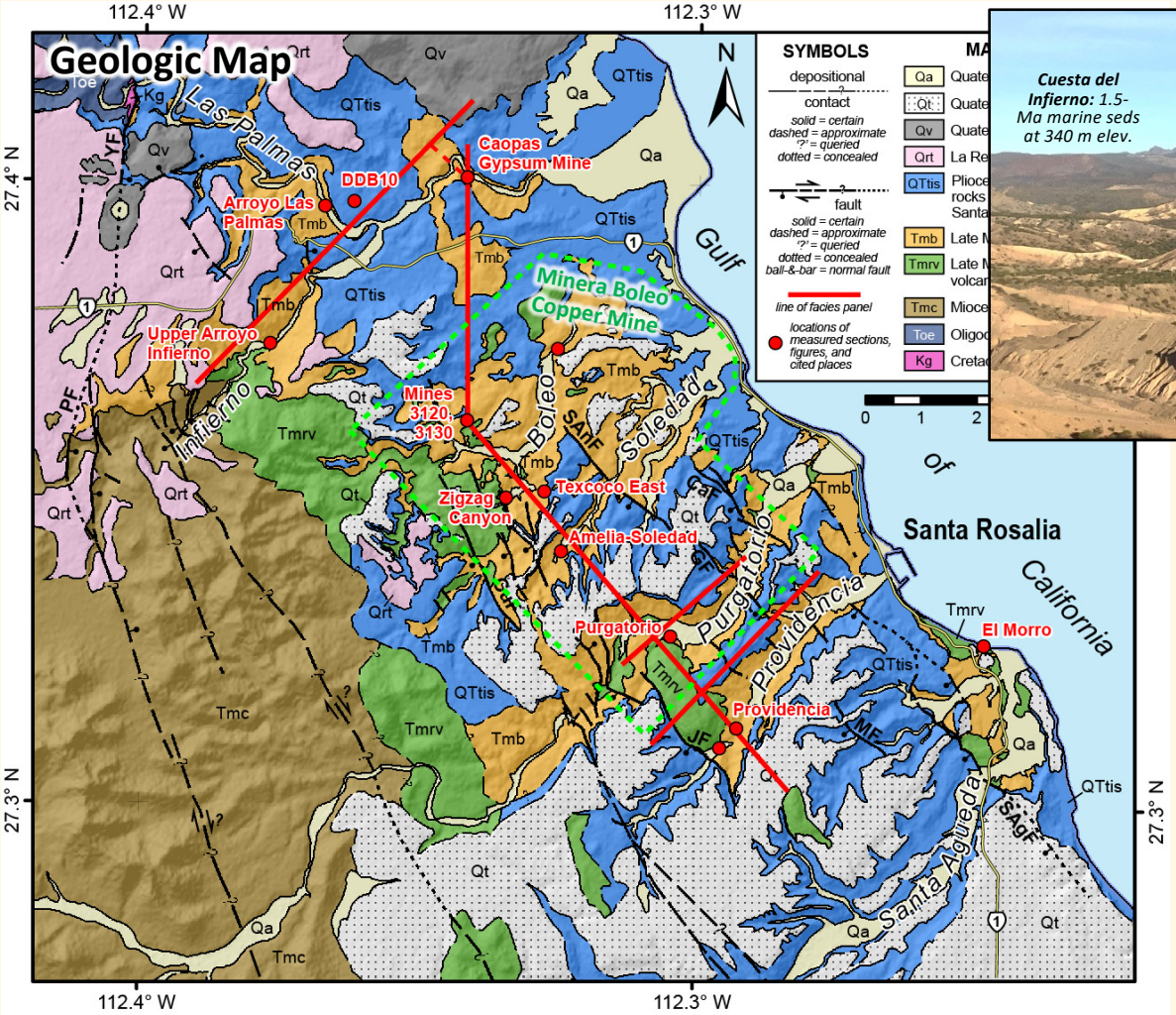
Pleistocene marine terraces, ages ca. 100 ka to ~1.4 Ma (Ortlieb, 1991; Schmitt et al., 2006)	Pb — Plio-Pleistocene magnesian andesites and basalts
Pleistocene terraces of uncertain age	Mb — Late Miocene (~12-9 Ma) post-subduction tholeiitic lavas, Nb-enriched basalts, adakites, and magnesian andesites
QTs — Paleocene to Holocene sedimentary deposits (incudes San Gregorio, Isidro, Ignacio Fms)	Mv — Comondú (early-mid Miocene) subduction-related volcanic rocks *AND* post-Comondú (late Mioc.) andesitic to basaltic rocks
Pv — Pleistocene calc-alkaline volcanic rocks	Pz-Mz — Paleozoic and Mesozoic plutonic and metamorphic rocks

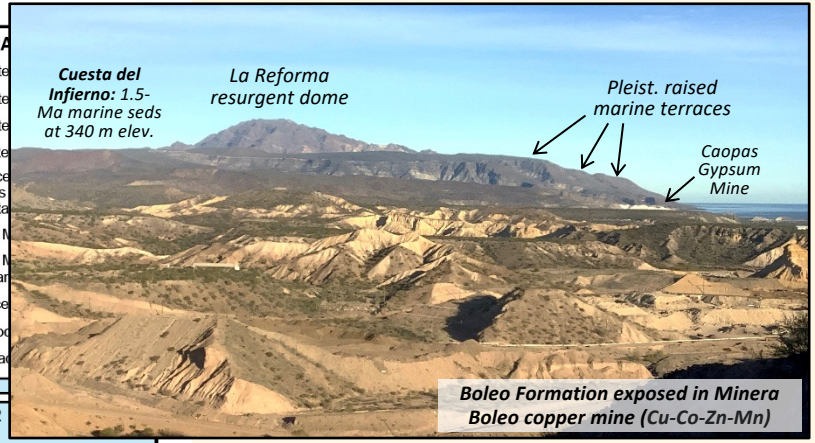
Geology of the Central Baja California Peninsula

- Miocene subduction-related volcanic/volcaniclastic rocks.
- Plio-Pleis. volc & sed deposits
- Belt of strike-slip & normal faults and fault-bounded basins in NE.

Santa Rosalía Basin

- 80-km long, late Mioc. to Pleist. sedimentary rocks.
- Latest Miocene Boleo Fm: initial marine flooding **~ 6.3 Ma**.
- Inverted/uplifted by La Reforma volcano starting ~ 1.4 Ma.





Boleo Formation

(1) Detrital Zircon Ages

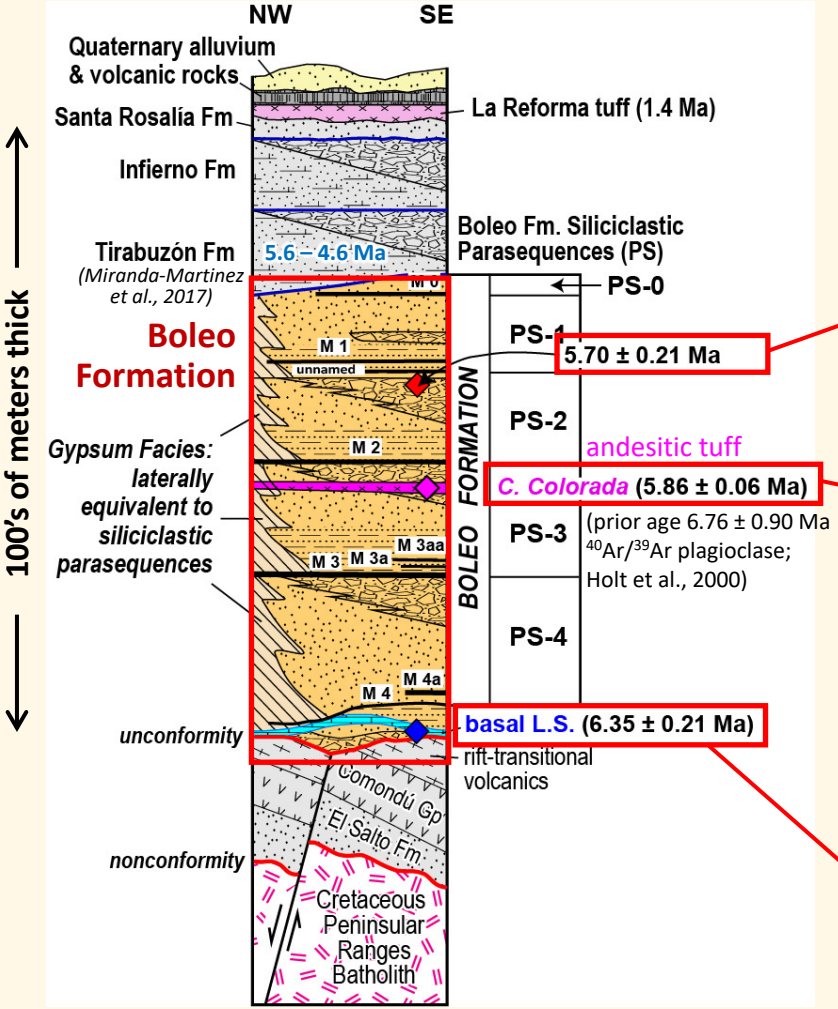
(2) Sedimentary Facies

(3) Stratigraphic Architecture and Growth Strata

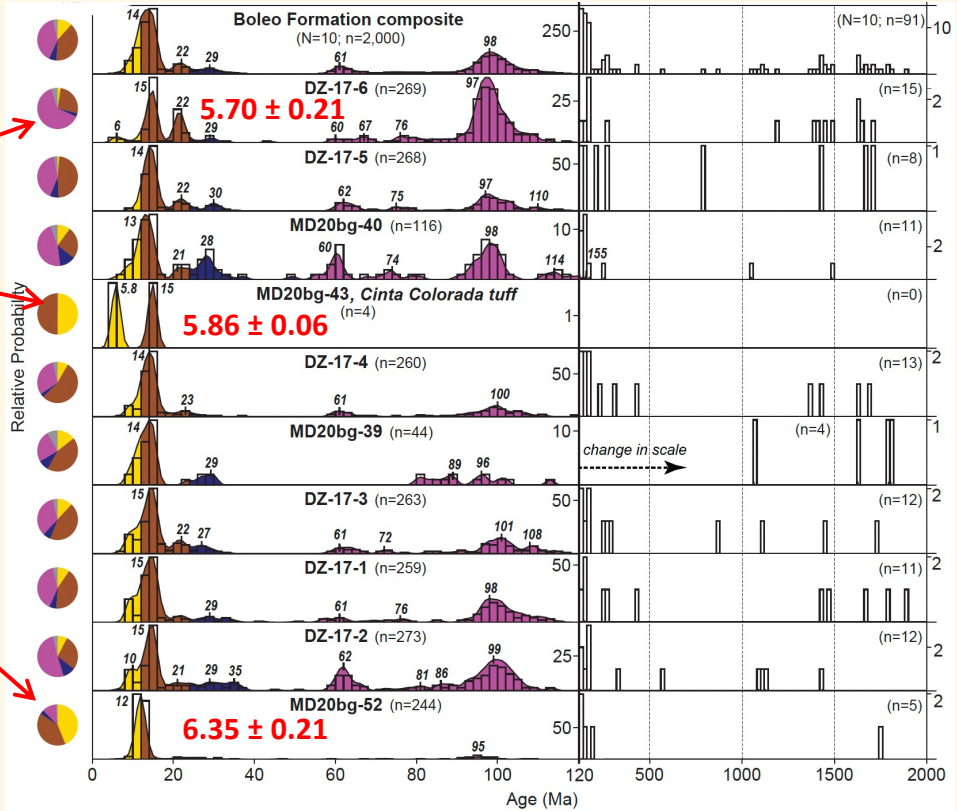
(4) Pull-Apart Basin Model

(5) Regional Marine Flooding at ca. 6.3 Ma

Santa Rosalía Basin Stratigraphy



Boleo Fm Detrital Zircon Ages *(Darin et al., in press)*



Boleo Formation: Sedimentary Facies Associations

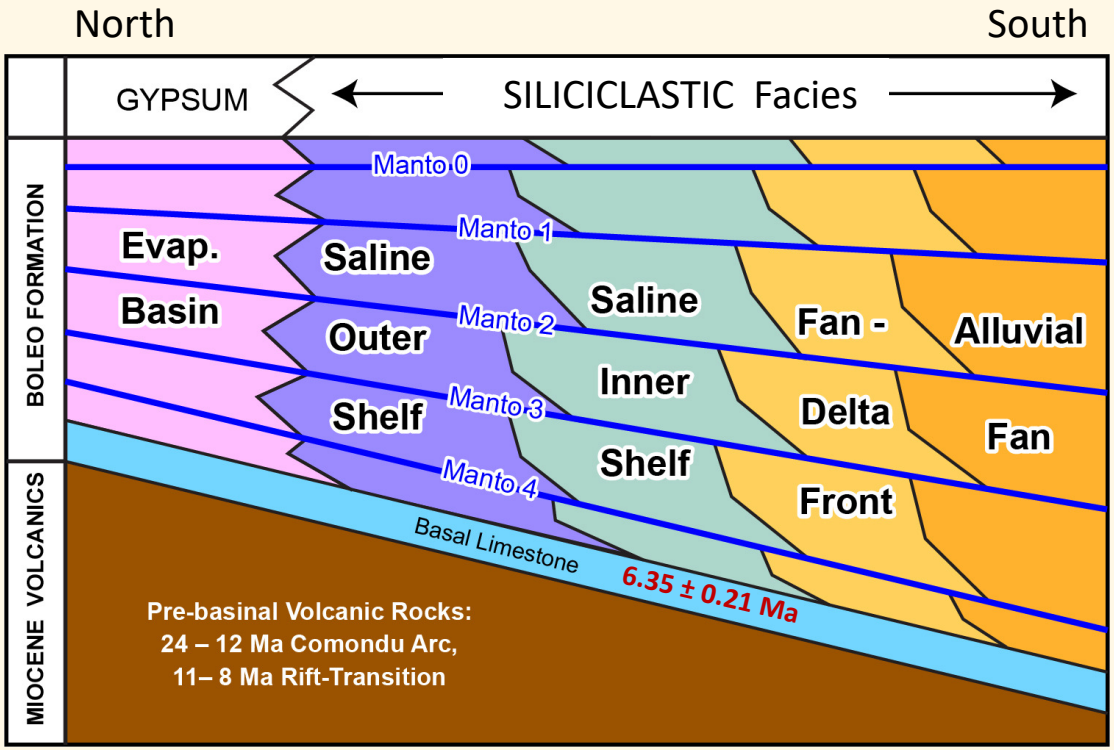
Facies Associations

4. Mantos (shale)**:** stratiform ore deposits
Rapid marine transgressions, hydrothermal activity, liquefaction.

3. Gypsum Facies: subaqueous & subaerial
Distal evaporite basin, subaqueous to subaerial, age-equivalent to deltas.

2. Siliciclastic Facies: C-up parasequences
Large input of sediment due to growth of topography in Baja peninsula.

1. Basal Limestone (~ 5 m thick)
Initial marine incursion into Gulf of California, localization of strain along the Pac.-Nam plate boundary.



Boleo Formation: Sedimentary Facies Associations

Marine Basal Limestone (thin, transgressive)

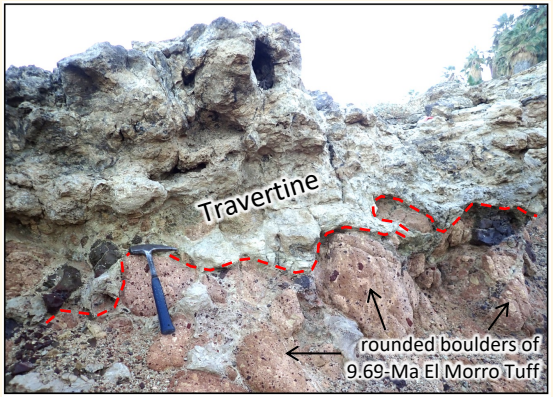
Travertine/Tufa/Stromatolites
Carbonate Shoreline

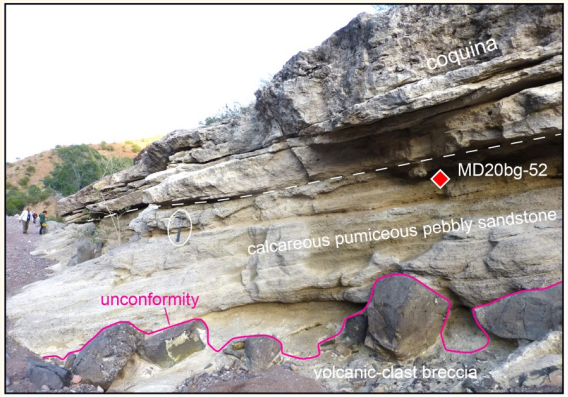
→

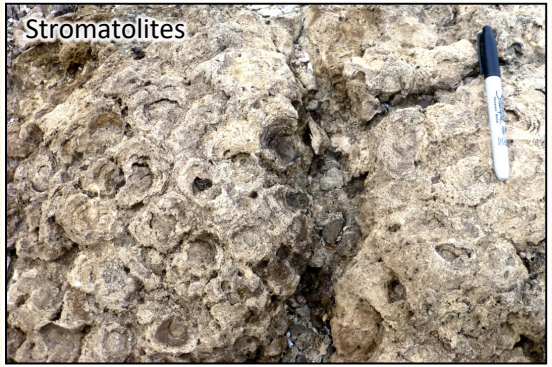
Calcarenite/Coquina
Nearshore Shelf

→

Molluscan Packstone
Offshore Shelf







Siliciclastic Facies

Coarsening-Up (delta progradation)

Code	Lithology	Summary Description	Interpret -ation
S1		Thin Shale Manto	Marine Flooding
		← MFS	
S5		Conglomerate	Alluvial Fan
S4		Interbedded Congl and Sst	Fan Delta Front
S3		Sandstone (X-bedded, bioturbated)	Saline Inner Shelf
S2		Heterolithic Facies	Saline Outer Shelf
S1		Thin Shale Manto	Marine Flooding
		← MFS	
S5		Conglom.	Alluvial Fan

MFS = marine flooding surface

Gypsum Facies (Salgado Muñoz and Niemi, in review)

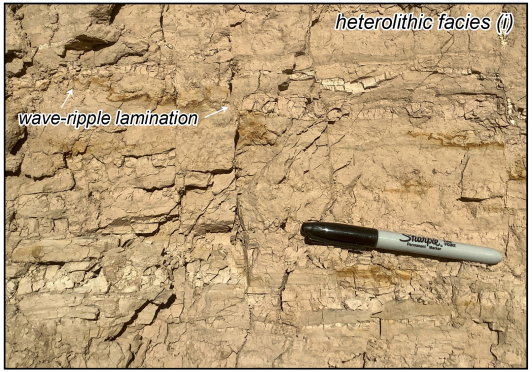
Shallowing-Up (basin desiccation)

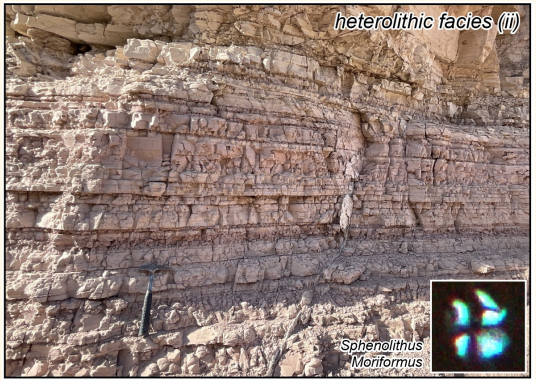
Code	Lithology	Summary Description	Interpret -ation
E1		Laminated Gypsum	Deep Evap. Basin
		← MFS	
E5		Gypsrudite (breccia)	Subaerial Exposure
E4		Mud-Gypsum Laminae	Subaerial Sabkha Flat
E3		Wavy Laminated Gypsum	Semi-Emergent Shoals
E2		Laminated Gypsum with Selenite Xls	Shallow Evap. Basin
E1		Laminated Gypsum	Deep Evap. Basin
		← MFS	
E5		Conglom.	Alluvial Fan

MFS = marine flooding surface

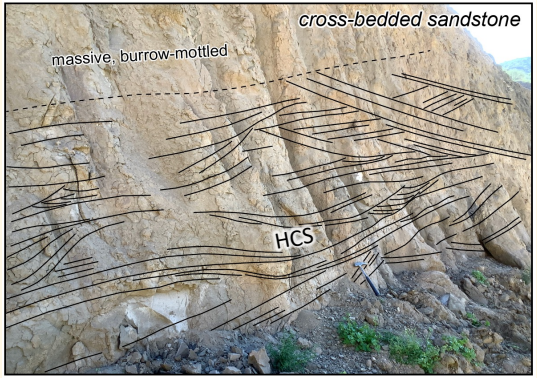
Boleo Formation: Sedimentary Facies Associations
SILICICLASTIC Facies

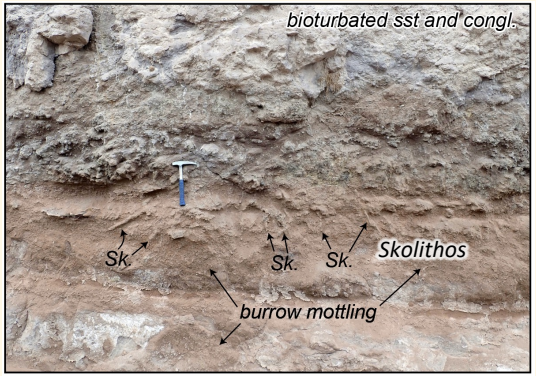
Mud-silt-sand heterolithic facies
Saline Outer Shelf



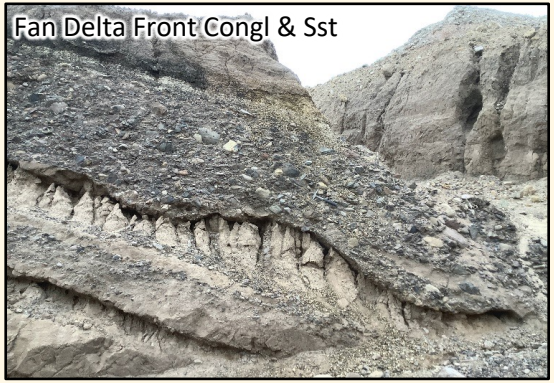


Cross-Bedded and Bioturbated Sst
Saline Inner Shelf



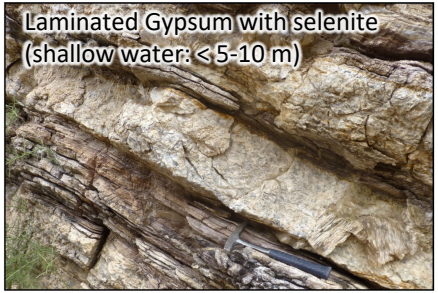


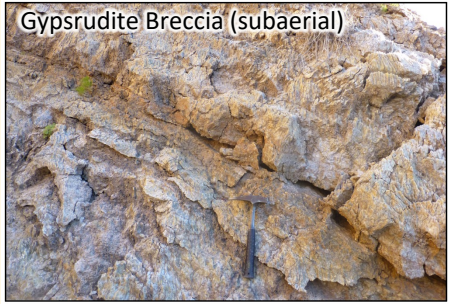
Channelized Conglomerate & Sst
Alluvial Fan & Fan Delta

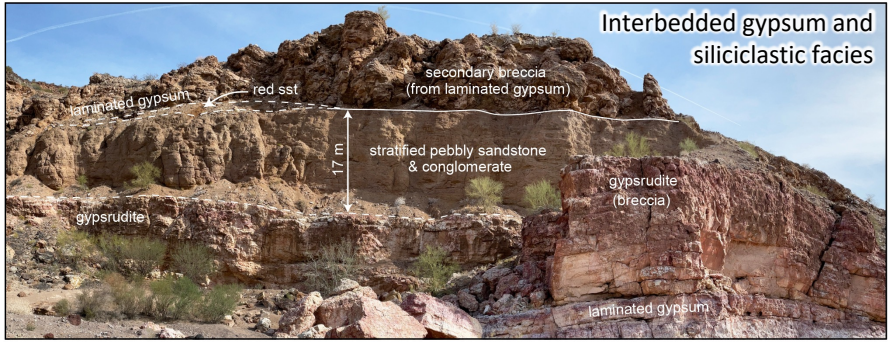


Boleo Formation: Sedimentary Facies Associations

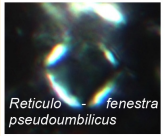
GYPSUM Facies

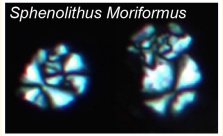


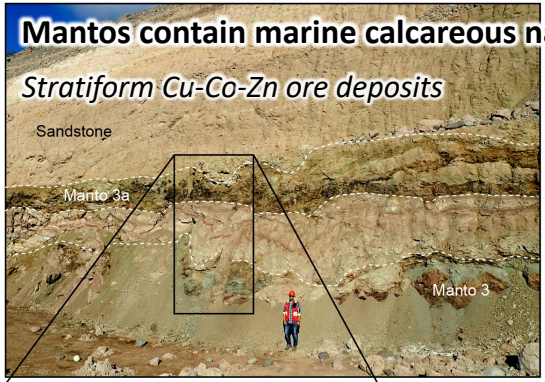


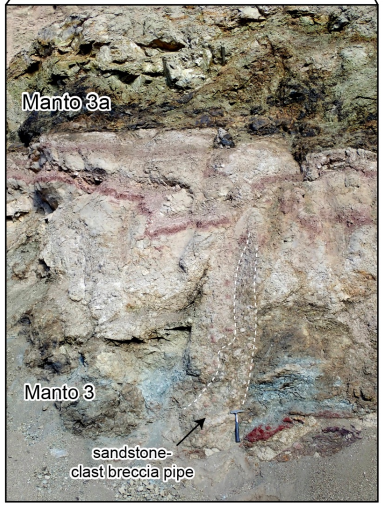


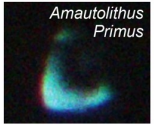
Thin Shale MANTOS (marine)

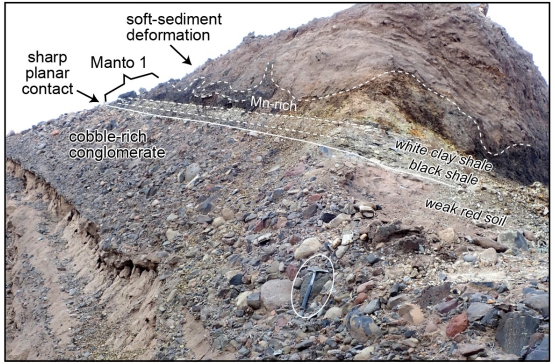




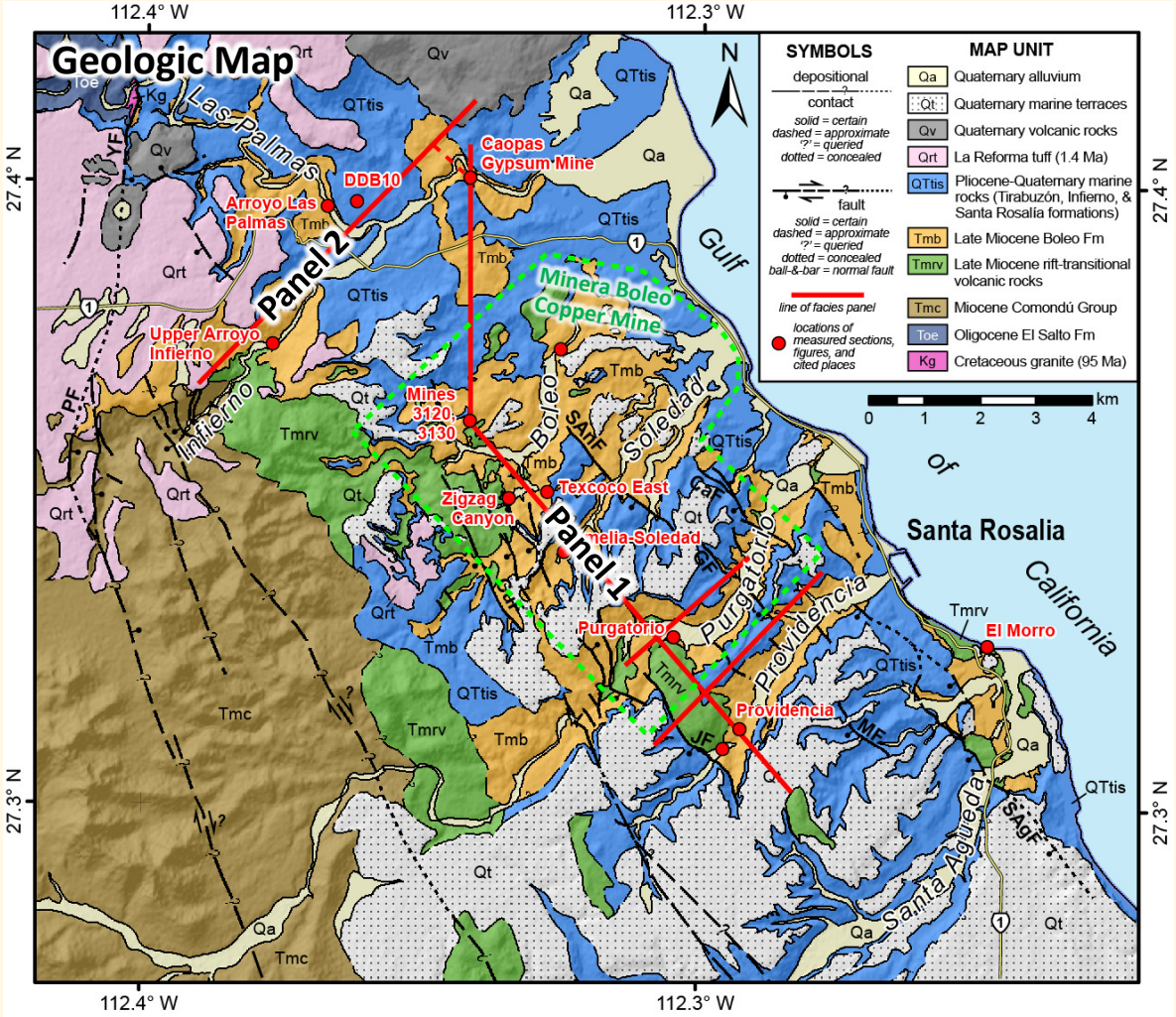






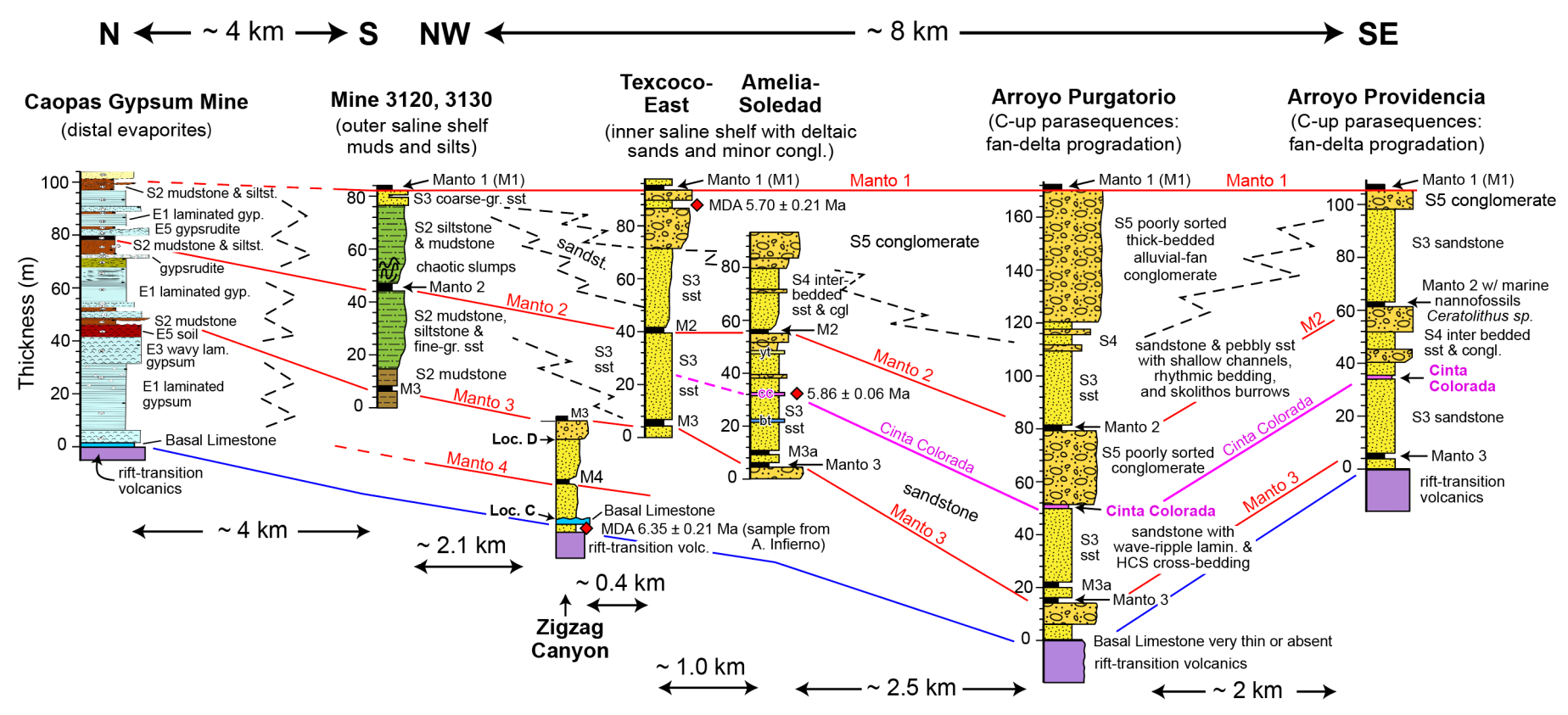


Stratigraphic Architecture and Growth Strata



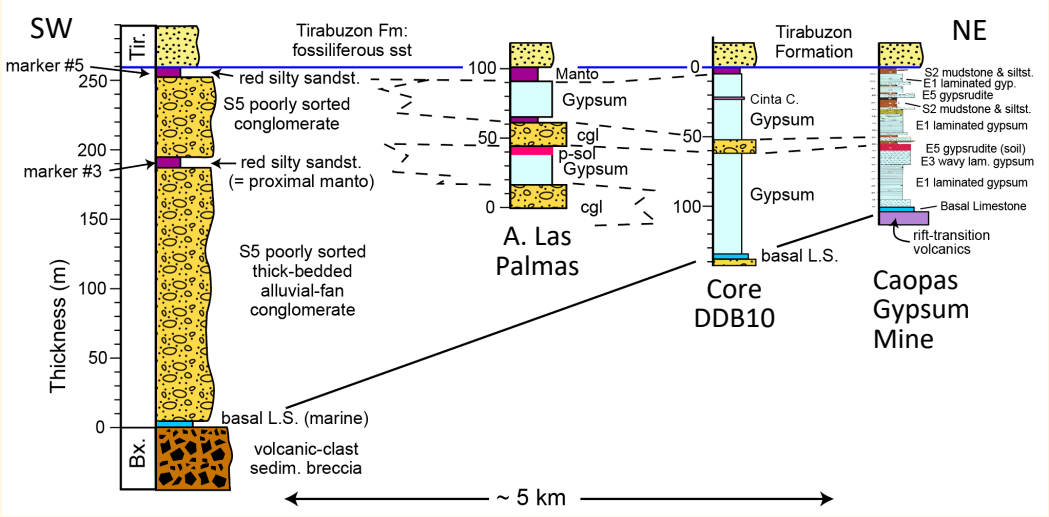
PANEL 1

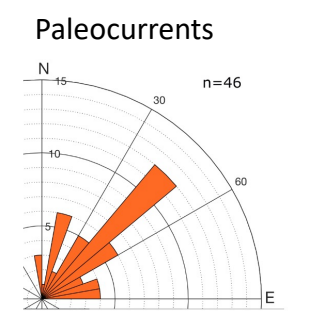
Boleo Formation



PANEL 2

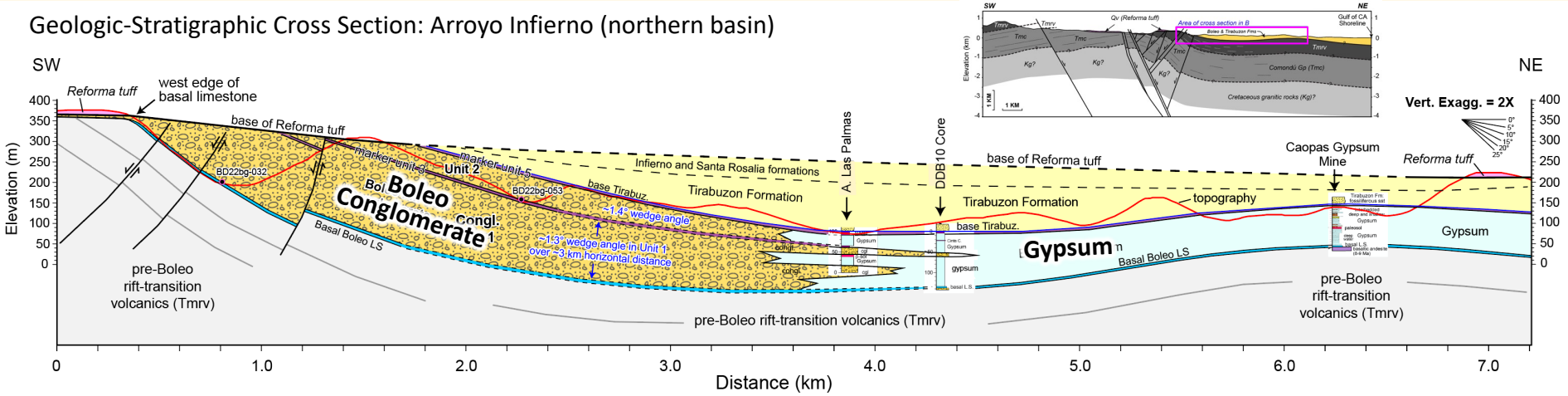
Boleo Formation: Arroyo Infierno



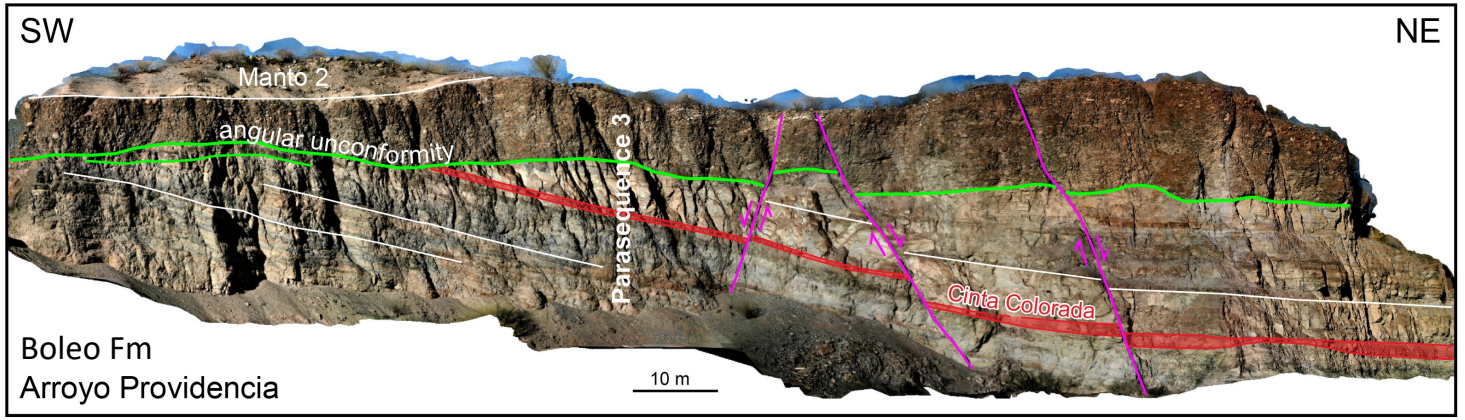


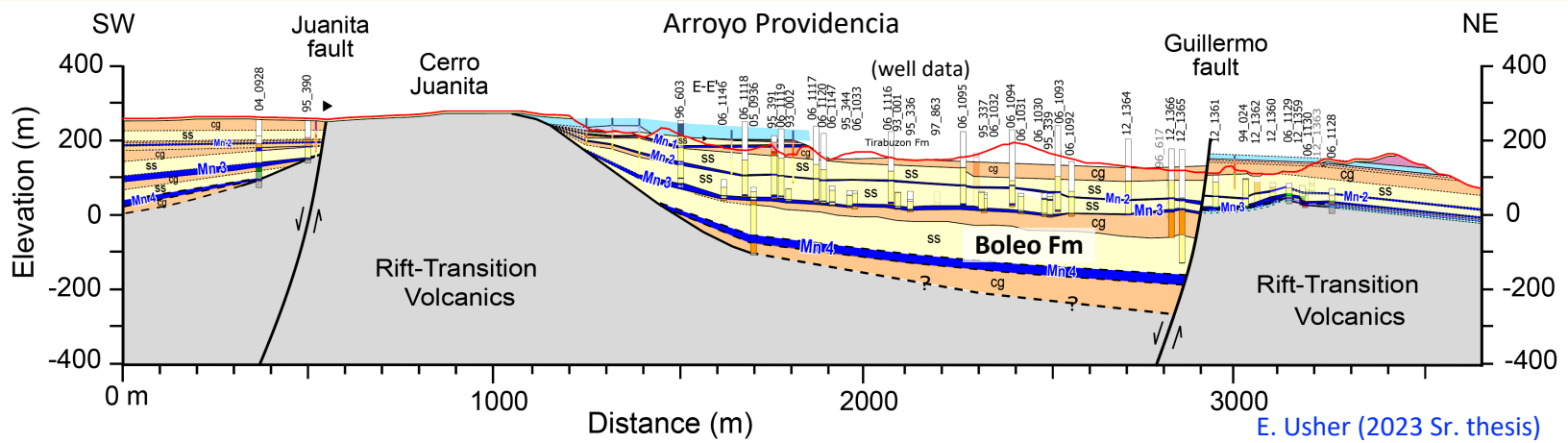
Clast imbrications: Gravel transport to NE

Geologic-Stratigraphic Cross Section: Arroyo Infierno (northern basin)

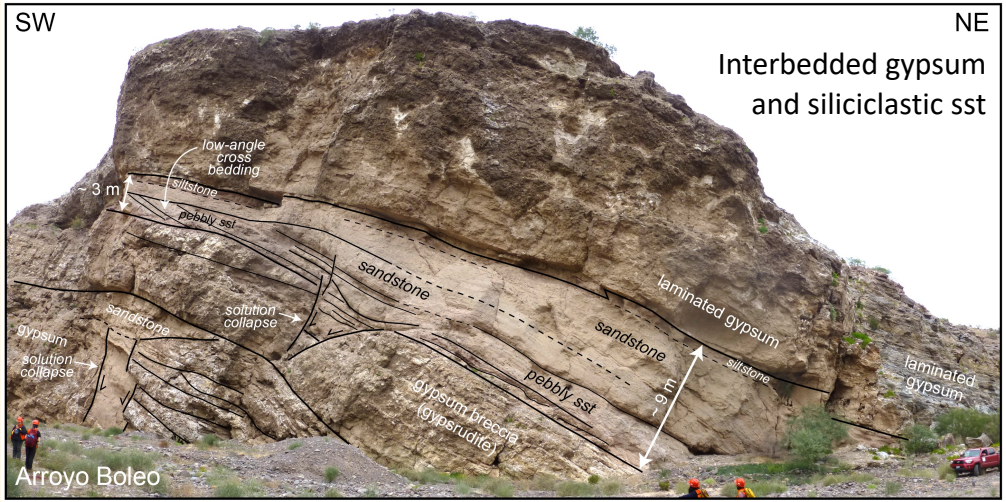


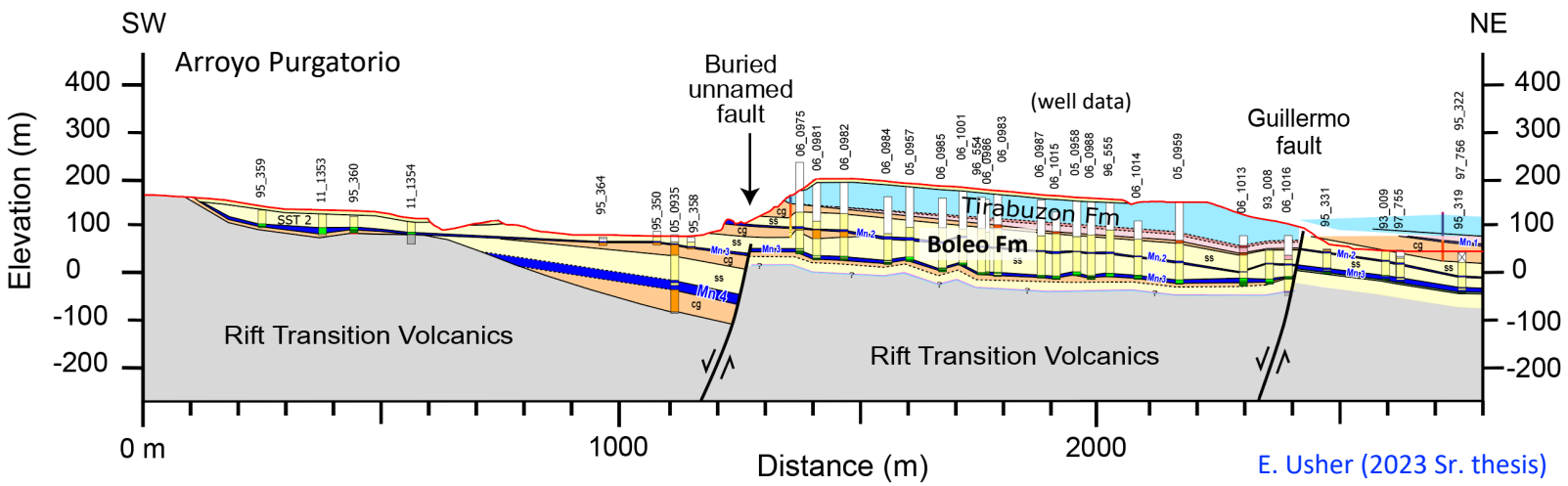
Syn-Depositional Growth Strata



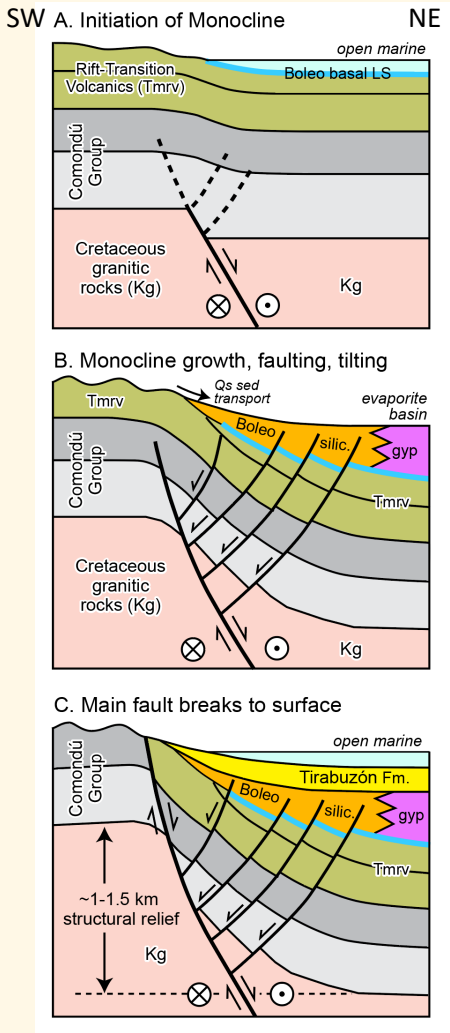


Growth Faults in Boleo Fm:
Record of syn-depositional faulting and tilting to NE





Monocline Growth: driver of syn-depositional faults



(A) Initiation of monocline above tip of oblique normal fault, marine flooding into subsiding basin, deposition of Boleo marine basal limestone.

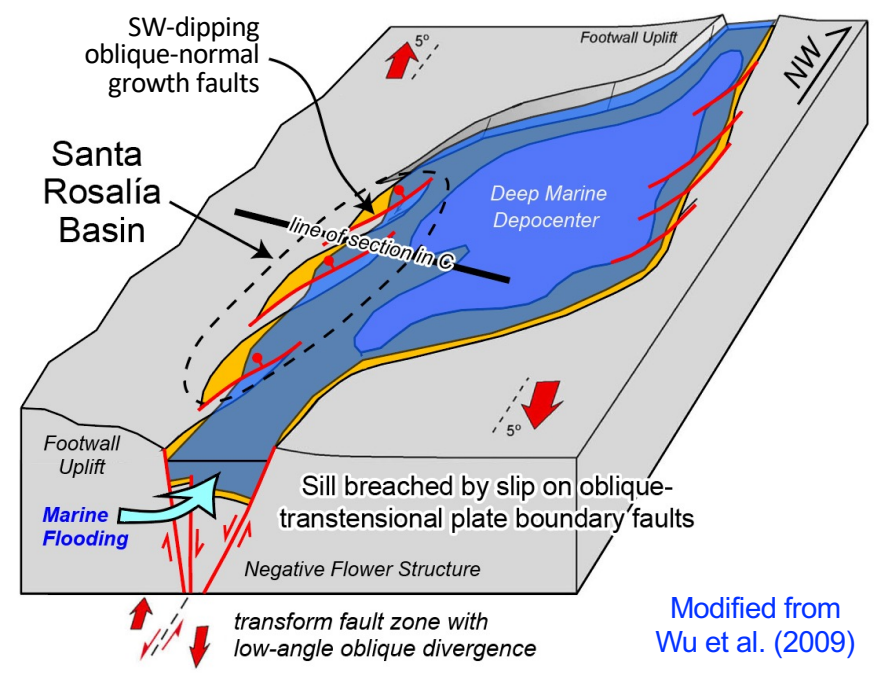
(B) Growth of monocline above tip of propagating normal fault, NE tilting on antithetic normal faults, continued subsidence, deposition of Boleo Formation siliciclastic (silic.) and gypsum (gyp) facies

(C) Main fault breaks to the surface, Tirabuzón Formation is deposited on top of older antithetic normal faults.

(adapted from Willsey et al., 2002; Jackson et al., 2006; Wilson et al., 2009).

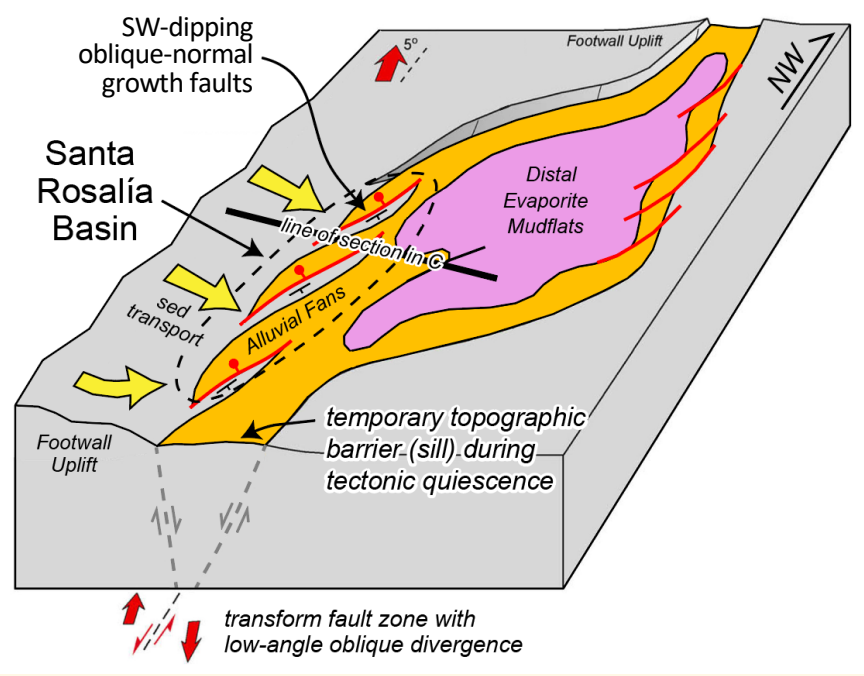
Transtensional pull-apart basin. Boleo Fm: two-stage response to episodic faulting

Stage 1: Transtensional faulting & rapid marine flooding, transgression. **Mantos** record hydrothermal activity.

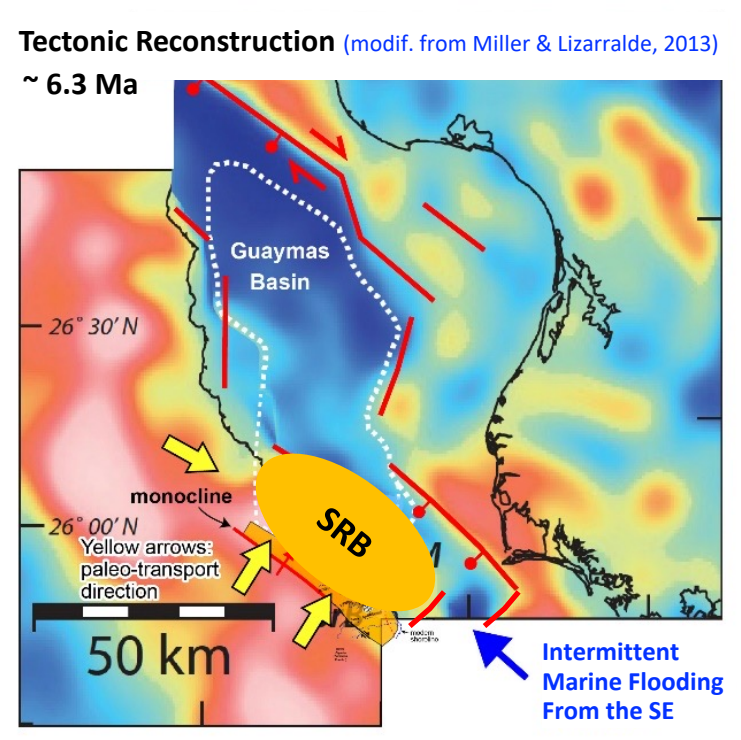


Modified from Wu et al. (2009)

Stage 2: Basin is isolated from the ocean. Evaporitive drawdown & progradation of alluvial fans and fan deltas into the basin.

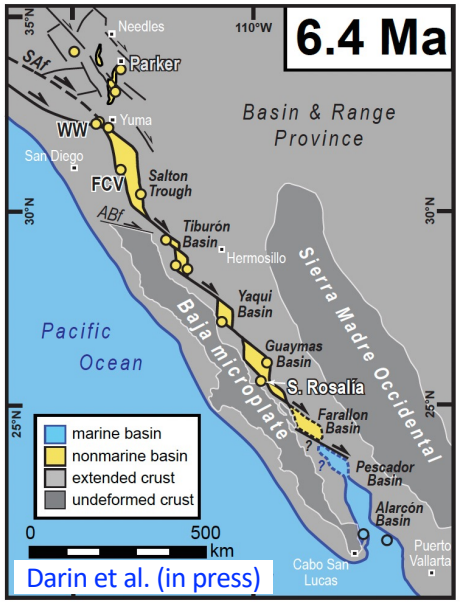


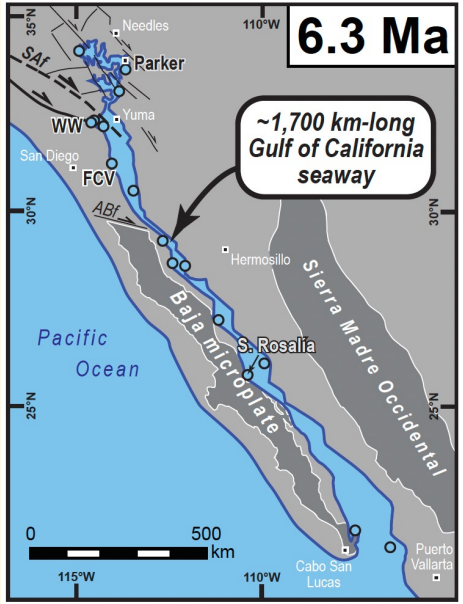
Basin Model (pull-apart basin)



Guaymas – Santa Rosalía Pull-Apart Basin during **onset of sea floor spreading.**

<u>Geologically Instantaneous</u> marine flooding into Gulf of California at ca. 6.3 Ma





<u>Marine flooding into pre-existing basins</u>: geologically instantaneous event (within age uncertainties) that inundated a >1,000 km lowland along the plate boundary from the central to northern Gulf of California and Salton Trough to the lower Colorado River valley in as little as ca. 100,000 years.

CONCLUSIONS

Late Cenozoic Tectonic History, Central Baja Peninsula – Three stages:

1) 30 – 12 Ma: Farallon plate subduction & arc magmatism (Comondú Gp)
2) 12 – 8 Ma: End of subduction, tectonic reorganization, oblique extension
3) ~ 8 – 0 Ma: Strike-slip motion in modern Gulf of California
   - **Latest Miocene Boleo Formation (Santa Rosalía Basin):**
     - Transtensional pull-apart basin
     - Mixed evaporite-siliciclastic sedimentation
     - Thin shale mantos: episodic marine flooding, seismicity, hydrothermal activity
   - Boleo Basal limestone records rapid **marine flooding at ~ 6.3 Ma,** during onset of seafloor spreading in Guaymas basin.
   - **Geologically "instantaneous"** marine flooding event inundated >1,000 km of plate boundary lowland in as little as ~ 100,000 years.