Syntectonic Deposition of Plio-Quaternary Sediments in the Santa Rosalía Basin of Baja California Sur, Mexico

by

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Under the supervision of Dr. Andrew Haveles and Dr. Tina Niemi

ABSTRACT

Plio-Quaternary sediments of the Tirabuzón, Infierno, and Santa Rosalía formations record syntectonic deposition in the Santa Rosalía basin—an oblique-rift-margin basin along the Gulf of California in Baja California Sur, Mexico. This study aims to further our understanding of the basin's evolution and reconstruct its depositional history through interpreting the tectonic events and depositional environments present at Mesa Soledad. This was done through the analysis of two stratigraphic sections on either side of a high-angle, NNW-striking fault with 26 meters of vertical displacement. Analyses of macrofossils, microfossils, sediments, and sedimentary petrography help characterize both the marine and fluvial facies within the three sedimentary units present in the study area: the Tirabuzón, Infierno, and Santa Rosalía. These three units lie unconformably atop one another, all with a distinct stratigraphic pattern of regression characterized by fossiliferous marine sandstones grading up into poorly-sorted fluvial conglomerates. The displacement seen in this previously unstudied area creates a mismatch of the stratigraphy across the fault, providing evidence of strike-slip and syntectonic subsidence and uplift.

ACKNOWLEDGEMENTS

Thank you to Minera Boleo for their hospitality and access to their property, the National Science Foundation for the funding that made this research possible, to the University of Missouri Kansas City for their hospitality and access to laboratory equipment, to Tina Niemi, Becky Dorsey, and Andrew Haveles for their advisement, and to Luke Johnson for being a supportive field research partner.

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INTRODUCTION

Studying continental rifts has been integral to understanding one of the most ancient mechanisms of our planet, plate tectonics. The Gulf of California ruptured over a tectonically-active margin, a southerly extension of the San Andreas Fault (Figure 1). The Gulf of California's oblique-divergent expansion is particularly interesting because of the relatively fast rupturing it underwent ~6-10 Ma (Umhoefer, 2011). This area has not been mapped within the framework of modern tectonic concepts, providing an exciting opportunity to study the evolution of a relatively young continental margin.

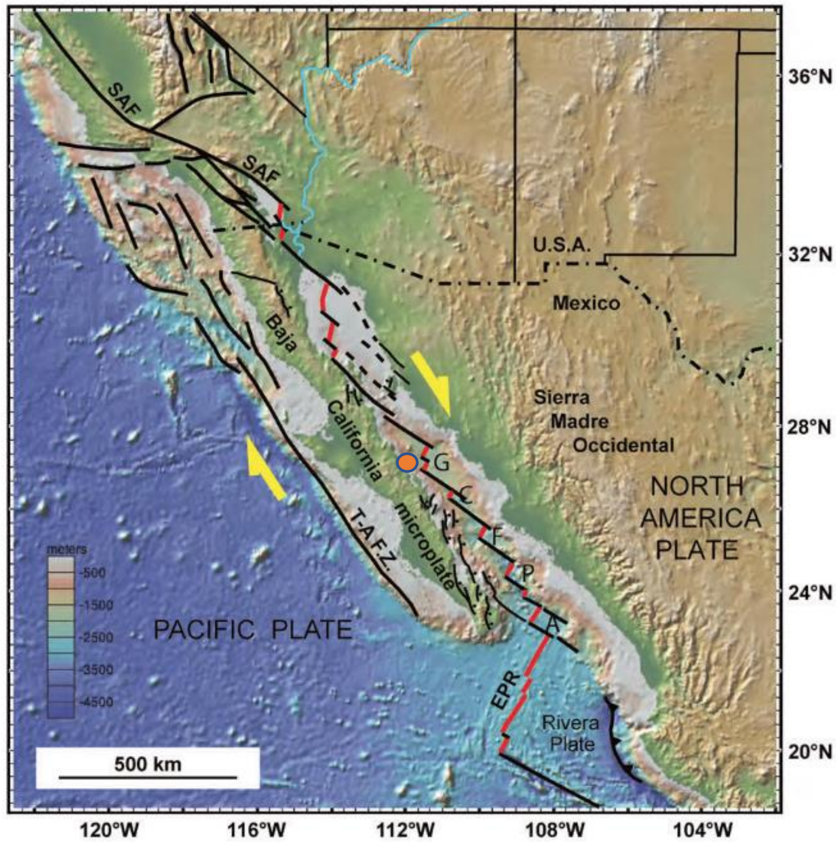

Figure 1: Tectonic map of the Pacific–North America plate boundary from Umhoefer, 2011. Location of study denoted in orange.

The Santa Rosalía basin in Baja California Sur, Mexico has been well-studied by many disciplines, including structural geology, volcanology, and sedimentology and stratigraphy. The most notable pieces of literature pertaining to the Santa Rosalía basin are the economic geology reconnaissance papers from Wilson and Veytia (1949) and Wilson and Rocha (1955). Their work detailed every aspect of the basin from the mining potential to the weather; but most importantly, they named and described the geologic formations of the basin. The three youngest formations described are found at Mesa Soledad, the Tirabuzón, Infierno, and Santa Rosalía, all of which record later phases of extension at Mesa Soledad and around the basin. While this research is not focused on economic geology like Wilson and Rocha's, their reconnaissance efforts laid the groundwork on which this project could be built, along with many more research efforts since, in the way of dating the expansion of the Gulf of California (Umhoefer, 2011), stratigraphy (Ochoa-Landín et. al., 2000 and Ortlieb and Colletta, 1984), volcanology (Conly et. al., 2005 and Schmidt, 1975).

This region has a unique geologic history rich with tectonic events, volcanic activity, uplift of Quaternary terraces, and ancient ocean cover. Evidence of all these processes are present throughout the basin and are especially prominent at Mesa Soledad (Figure 2), an outcrop created by the active mining processes at Minera Boleo just outside of Santa Rosalía. This is an ideal location to study the evolution of a rifted continental margin because of its accessibility as a result of the mining operations taken place there, along with the opportunities relating to understanding the stratigraphic history and rifting processes exposed at such outcrops. This study determines the relationships between faulting, deformation and deposition and creates a higher-resolution stratigraphic record of Mesa Soledad. This was done through measuring and observing over 65 meters of section, analyzing the lithologic and paleontologic samples taken, and inferring a depositional history of the Mesa.

Mesa Soledad has not been measured and described in such high-resolution as it is in this study, primarily because it is a recent exposure as a result of Minera Boleo's strip mining processes, and it may not have been exposed whilst past stratigraphic research was being conducted. However, with the progress of the mining to date, it is possible the outcrop may be destroyed to advance further mining endeavors on the property. This provided an opportunity to gain previously unattainable insight into the syntectonic—in synchronization with tectonic events—processes at work in the Santa Rosalía basin.

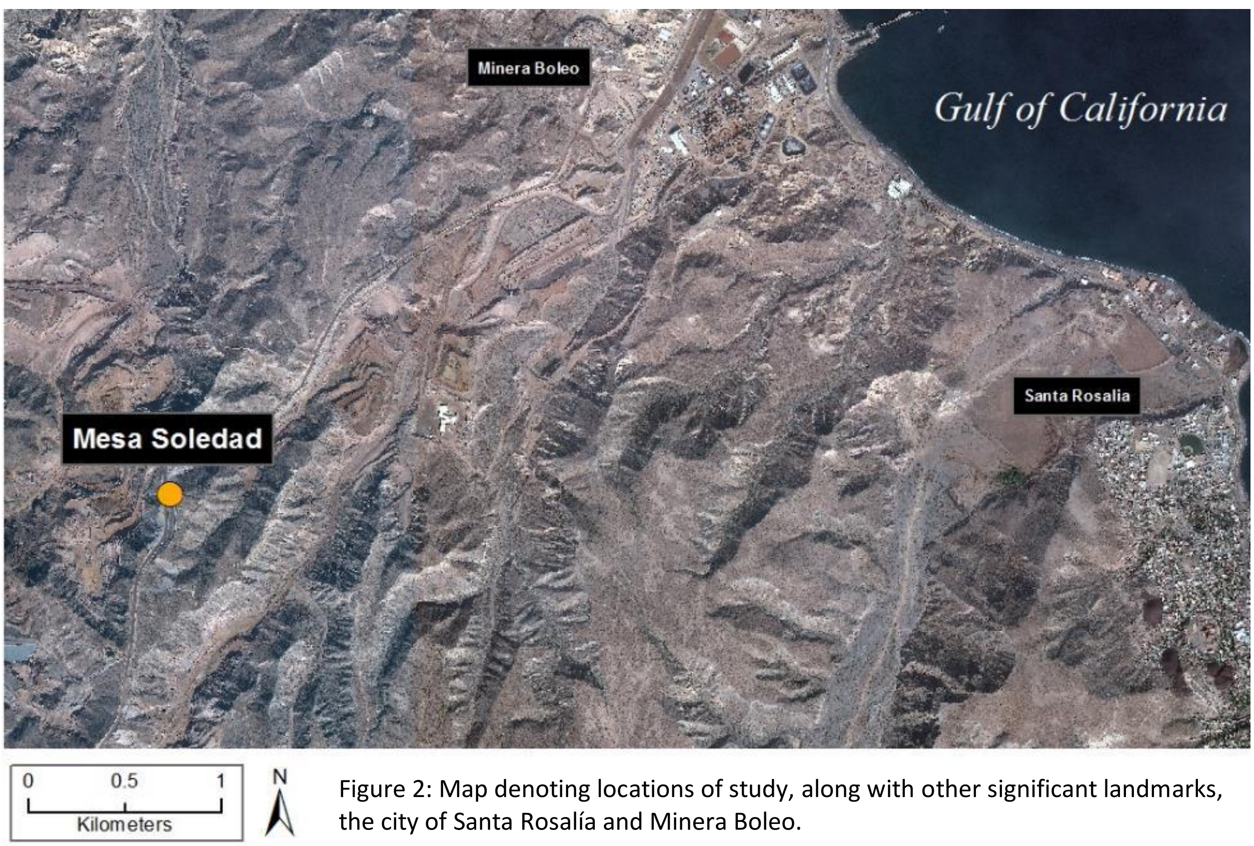

Figure 2: Map denoting locations of study, along with other significant landmarks, the city of Santa Rosalía and Minera Boleo.

Geologic Setting

The Baja California peninsula remained a part of what is now mainland Mexico until approximately 12 Ma, in the Miocene, when it began to rupture as a result of strike-slip displacement (Dorsey and Burns, 1994). The southernmost portion of the Gulf of California separated from mainland Mexico ~6-10 Ma. through a rapid rupture as a result of hot, weak lithosphere, high strain from relatively quick plate motion, and large pull-apart basins from dominant strike-slip faulting creating thinning crust (Umhoefer, 2011). The expansion is ever-increasing, with a relative plate motion of ~45-47 mm/yr between the Baja California microplate and the North American plate (Plattner et al., 2007). This southern extension of the San Andreas Fault has an oblique-divergent setting, a previously active tectonic setting that remains consistent within the Santa Rosalía Basin.

The region's basement rock is a sparsely-outcropping quartz monzonite, dated at 91 Ma (Schmidt, 1975). It is overlain by the Miocene-aged Comondú volcanics, which document the shift from subduction to proto-rift extension with associated volcanism, between 12 and 8 Ma. After the volcanic activity ceased, the Santa Rosalía basin began an interval of rapid subsidence. The resulting basin was filled by the ore-bearing Boléo Formation, Pliocene to Pleistocene aged sedimentary rocks, which lie unconformably atop the Comondú volcanics (Figure 3). These ore deposits are the reason mining operations, like the Minera Boleo copper, cobalt, zinc and manganese mine, have been set up in this region. Four repeating stratigraphic sequences within the El Boléo are designated as "Mantos", defined by a layer of laminated copper-claystones (< 2 m) beneath up to 20 meters of upward-coarsening breccia, capped by another laminated claystone layer with iron and manganese oxides (Conly et. al., 2005), deposited in a partially marine, partially nonmarine environment, as suggested by the deltaic interfingering of marine and nonmarine deposits (Wilson and Rocha, 1955). The three units documented for the purpose of this study lie unconformably above the El Boléo: The Tirabuzón Formation, Infierno Formation, and the Santa Rosalía Formation (Figure 4).

As observed around the basin, but not at Mesa Soledad, the Tirabuzón rests unconformably on the El Boléo Formation, deposited during the Early-to Mid-Pliocene (Ortlieb and Colletta, 1984). The Tirabuzón was previously referred to as the Gloria Formation by Wilson and Rocha (1955) but will herein be referred to as the Tirabuzón Formation. The notation switch came to be as the name “Gloria” was already in use for a formation in a nearby basin at the time of their study. Marine carbonates, sandstones, and beach deposits grade up into fluvial conglomerates within the Tirabuzón (Figure 4). The Late Pliocene Infierno Formation lies unconformably above the Tirabuzón Formation (Wilson, 1949), characterized by a similar pattern of marine carbonates, fossiliferous sandstones, and beach deposits grading up into continental conglomerates. Another unconformity forms the boundary between the Infierno Formation and the Santa Rosalía Formation, the uppermost formation seen at Mesa Soledad. This Pleistocene-aged unit (Wilson, 1949) records a similar regressive pattern involving basal fossiliferous sandstones grading upwards into terrestrial conglomerates.

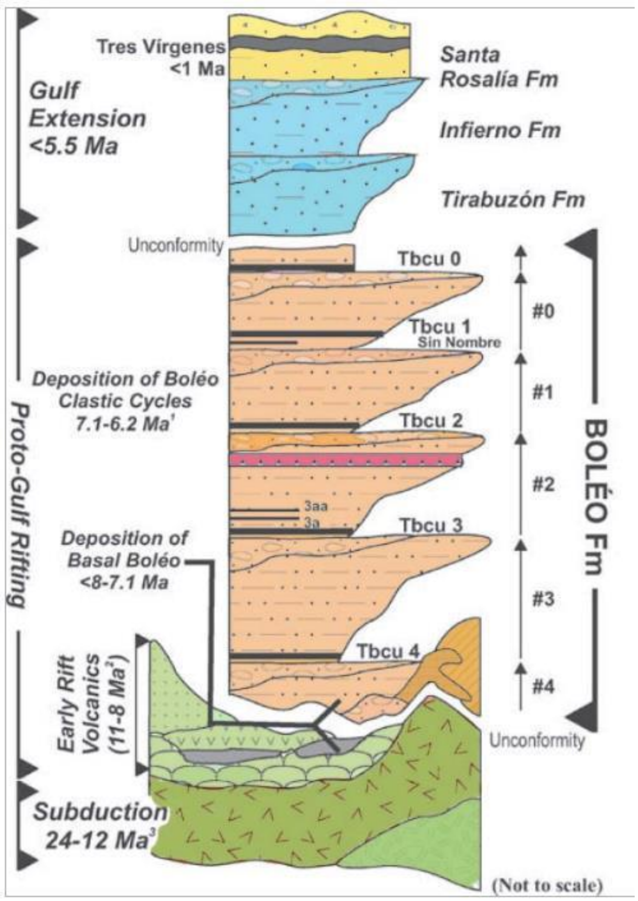

Figure 3: Idealized stratigraphy from Conly et. al., 2005, figure modified by Luke Johnson.

A high-angle, NNW-striking oblique normal fault with an apparent vertical displacement of at least 26 meters cuts through the Mesa Soledad outcrop, creating visible displacement in the Tirabuzón and Infierno formations, but the Santa Rosalía Formation extends across the fault and is not displaced by it. It is inferred that there is some amount of lateral displacement as a result of the faulting event, but the necessary means of measuring such displacement were not available at the time of study.

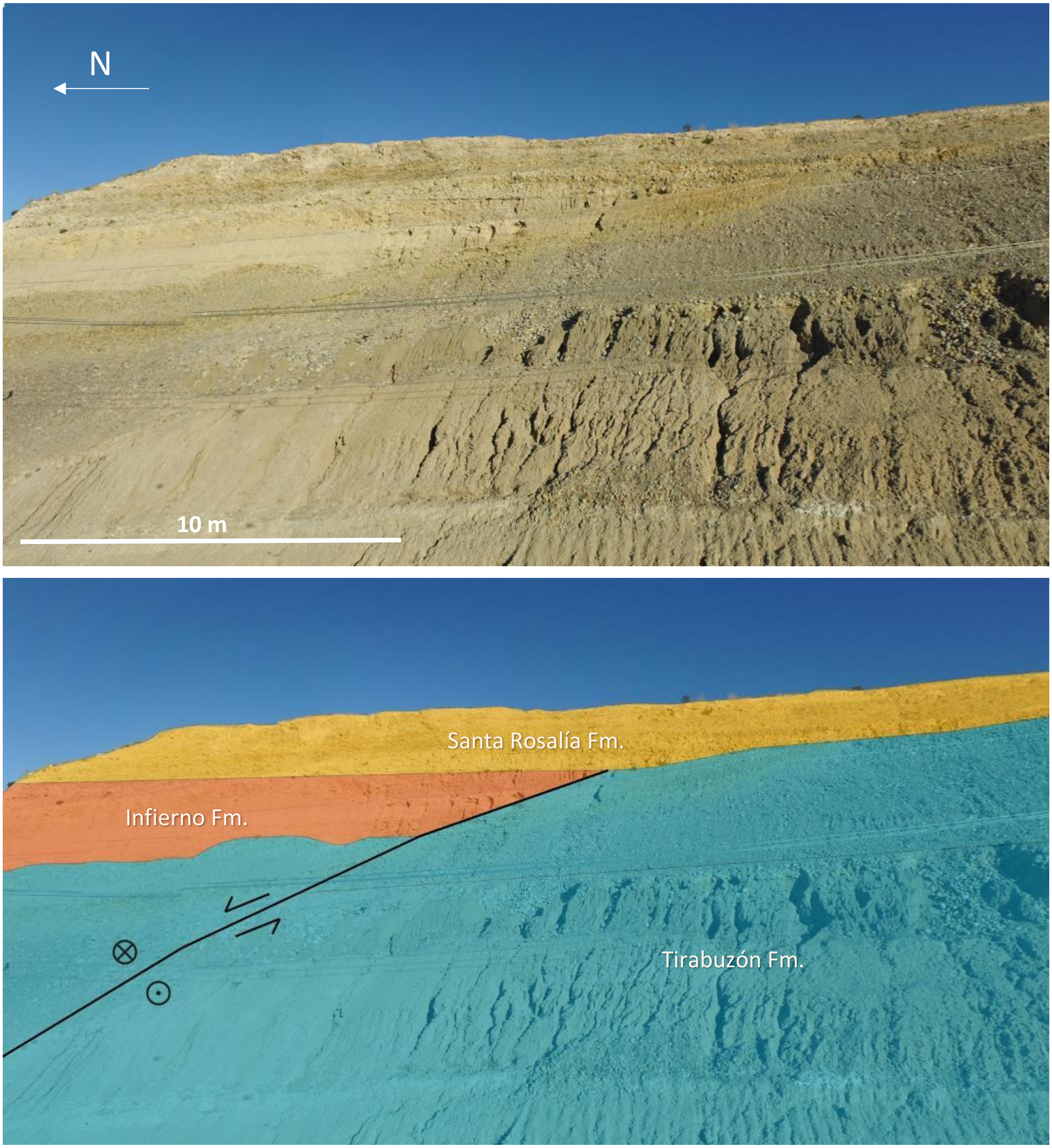

Figure 4: Top: uninterpreted photo of Mesa Soledad. Bottom: Photograph of the outcrop interpreted with the three different formations, and the oblique normal components of the fault annotated.

RESEARCH METHODS

Field Methods:

Field work in the Santa Rosalía basin was completed in January of 2017. To determine the paleoenvironments of the units present, two stratigraphic sections were measured on either side of the fault, one to the north and one to the south. Sixty-six meters of outcrop were logged in total; thirty-one meters to the north, representing all three formations and thirty-four to the south, representing the Tirabuzón and Santa Rosalía formations, not the Infierno. Field descriptions of grain size, sorting, and composition were made, along with bed thickness measurements, and documentation of various sedimentary structures and fossils. Disconformities between the three units present at Mesa Soledad were identified in the field, as well as one significant lag deposit on the south side. The disconformities were marked by changes in lithology, primarily a poorly-sorted conglomerate in contact with fine-grained, fossiliferous sandstones.

Samples of unconsolidated sediments, sedimentary rocks, and fossils were collected *in situ*. Our sampling strategy was to sample some of each facies change we described, with samples acquired randomly within a bed. There was an exception of some fossils that had eroded out of their original strata and were thus collected in-float. The in-float fossils' original strata were identified and measured, but the eroded-out fossils—large *Patinopecten* shells—were taken as a sample because of their well-preserved nature and accessibility. Thirty-two bulk samples were taken in total, with twenty-one taken from the northern section and eleven from the southern section. Strike and dip measurements of the fault were made with the FieldMove Clino application for iOS.

Laboratory Methods:

The unconsolidated sediment samples were dry sieved to increments of > 2 mm, 1 mm, 500 µm, 250 µm, 125 µm, 63 µm, and pan. The <125 µm size fraction from each sample was wet sieved, dried, and examined for microfossils. Microfossils were separated from other sediments under a binocular microscope and then transferred to cards for scanning electron microscope (SEM) analysis. Macrofossils were identified in the field to the class level, where the foraminifera were identified with the aid of resources from the Forminifera.eu-Project and KeyToNature's Marine Species Identification Portal online.

Fifteen thin sections were created from the consolidated samples, and petrographically analyzed using optical microscopy for different carbonate textures and microfossils. These fossils and carbonate structures were identified to aid in paleoenvironment determination, based on Folk's classifications (1959, 1962).

RESULTS

Between the two stratigraphic sections logged at Mesa Soledad, three formations are present; the Tirabuzón, Infierno, and Santa Rosalía formations. The exposure north of the fault present contains all three formations, whilst the southern section has only two, the Tirabuzón and Santa Rosalía. The facies described have been generalized in Table 1.

FIELD RESULTS - SOUTHERN SECTION

The southern half of the outcrop has the stratigraphic bottom at Mesa Soledad, beginning with the oldest formation, the Tirabuzón. The base of the section contains 3.2 m of fossiliferous, fine-grained sandstone, containing *Pecten* shell fragments, broken Echinoidea body fossils, internal molds of gastropods and other bivalves as well as burrow traces. This sandstone grades into a fine-grained sandstone with angular grains and more abundant bivalve molds, containing distinct pebble beds at 1.5 m, 2.8 m and 3.9 m. A single facies of well-cemented coquina facies with a maximum thickness of 1 meter lies above both fine-grained sandstones, pinching out to the south, away from the fault. Fine-grained sandstone similar to the aforementioned sandstone units continues for another 3.25 m above the coquina, maintaining the same gradual change from the Echinoidea-rich sandstone—the tests found are now well-articulated—into less-fossiliferous sandstone. One meter of well-sorted, clast-supported, cobble sized conglomerate sits on top of both sandstone units, one with well-articulated echinoids and one without.

Above this conglomerate sits an extremely well-sorted, matrix-supported pebble bed with clear imbrications (Figure 7D). This pebble bed pinches out to the north, towards the fault. Closer to the fault, at the same stratigraphic latitude as the pebble bed, is a poorly-lithified medium-grained sandstone with a clear cobble horizon at its base. This sandstone continues 3.2 m above the cobble bed; it grades laterally into a poorly-sorted, clast-supported conglomerate 10 m thick, and then grades vertically into a matrix-supported conglomerate, 6.5 m thick. All clasts within the two conglomerates are rounded, ranging in size from medium sand to cobbles; however, the clasts within the matrix-supported conglomerate appear to be more weathered (e.g., weathering rings present on broken clasts, exfoliation causing the clasts to crumble to the touch) than the underlying clast-supported conglomerate. The clasts seen across the conglomerate facies are almost entirely volcanic. One meter of poorly sorted, matrix-supported conglomerate with sub-angular clasts, ranging in size from fine sand to cobbles lies above. Atop this sub-angular conglomerate sits a very poorly-sorted, sub-rounded clast-supported conglomerate. These units form the top of the 29.5 m-thick Tirabuzón Formation at this locality.

The Santa Rosalía Formation rests disconformably on the Tirabuzón formation at this locality, which grades vertically into a coquina rich in bivalves and varieties of gastropods. Well-rounded, glassy mafic pebbles are found scattered throughout. The uppermost facies of the Santa Rosalía is a carbonate-rich, conglomeritic sandstone with no macrofossils. The Santa Rosalía is approximately 1.5 meters thick on the southern side of the exposure.

Field Results - Northern Section

The base of the northern Tirabuzón is 12.8 m of massive, clast-supported conglomerate, with 2.70 m of massive, matrix-supported conglomerate lying above it. These conglomerate units are poorly sorted, with clasts ranging from medium sand to cobbles, all rounded to well-rounded. A medium-grained sandstone covered in wash from above units (2.00 m) is atop the conglomerates. The sandstone grades upwards into another well-rounded, matrix-supported, rusty-colored conglomerate (2.6 m), where it forms the base of a disconformity with the Infierno Formation.

The wavy unconformity present between the Tirabuzón and Infierno Formations separates a poorly-sorted conglomerate and a fossiliferous, carbonate-rich, medium-grained sandstone. This facies pinches out away from the fault, and has a maximum thickness of 2.50 m. Body fossils of echinoids, gastropods, bivalves, and barnacles are found, along with cemented burrows(?), molds of gastropods and various shell fragments. Another sandstone is found above, characterized by large, well-preserved *Pecten* shells, more cemented burrows, and poorly-sorted grains ranging from fine to coarse sand (2.50 m). The sandstone overlying this *Pecten*-bearing facies is similar in sediment composition and ichnofossil content, but does not carry body fossils of any kind (0.50 m). A well-cemented sandstone sits atop the previous facies, with even more bioturbation. The well-cemented ichnofossil found within this facies altered the color of the rock from a light, tawny brown to a pale cream color (0.30m). Above the heavily-bioturbated facies is 0.30 m of course, poorly-sorted sandstone ranging in grain size from medium sand to pebbles, small (0.50 cm diameter), vertically oriented burrow grooves were found in this facies (Figure 7C). The next facies is poorly-sorted with larger (1.00 cm diameter) burrow casts and broken shell fragments. The grains range in size from medium sand to sub-angular pebbles. A 0.25 m-thick facies of poorly-sorted, primarily medium-grained sandstone lies above with inversely graded pebbles. A 0.35 m–thick muddy sandstone with mud cracks on the outcrop surface is above the inversely-graded sandstone (Figure 7B). The muddy facies pinches out towards the south, away from the fault. A 0.25 m-thick facies of heavily bioturbated, medium-grained sandstone rests above the muddy facies. This thickens to the south, compensating for the thinning bed of muddy sandstone that underlies it. A lens of calcareous and bioturbated sandstone, with a maximum thickness of 0.6 m, is visible in the outcrop, but is not laterally continuous. Mollusk imprints were found in this facies. Above both the calcareous sandstone lens and the medium-grained, bioturbated facies lies 3.5 m of matrix-supported conglomerate. The clasts are poorly-sorted, varying from medium sand to sub-rounded cobbles. Another facies of matrix-supported conglomerate is above the former with an orange, oxidation-like staining. Above this conglomerate is a disconformity between the Infierno Formation and the Santa Rosalía Formation.

The first facies of the Santa Rosalía is a fossil rich, brown-colored coquina (0.5 m) with gastropod and bivalve casts and molds. Above the brown coquina lies a 1.0 m-thick matrix-supported conglomerate rich in pebble-sized pumice clasts, all of which are sub-rounded to angular. Another poorly-sorted conglomerate pinches out to the north. This clast-supported facies has many glassy, mafic pebbles, all well-rounded (0.3 m, Figure 7A). Finally, a fossiliferous, matrix supported conglomeritic sandstone caps the Santa Rosalía Formation (1.5 m thick). The richest apparent abundance of fossils were found within this facies: bryozoans, bivalves, gastropods, and barnacles were all present (Figure 6).

Tectonics

The fault present at Mesa Soledad is a normal fault, oriented N 23° W with a dip of 69° (Figure 5). The northern side of the outcrop is the hanging wall, which moved down in respect to the footwall to the south. There is an observable dextral lateral component, but it was not quantifiable with the resources available in the field. At least 26 m of vertical displacement was caused by the faulting event, as seen in the separation of the Tirabuzón facies.

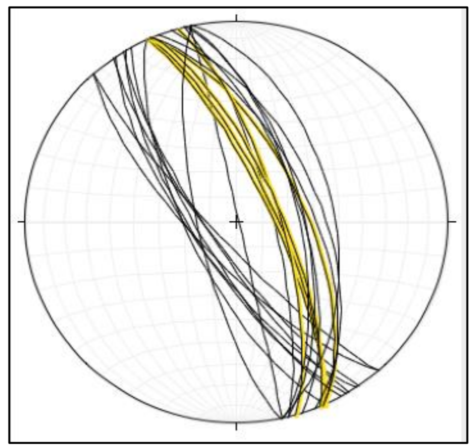

Figure 5: Stereonet of faults in and around Mesa Soledad, all found in the Tirabuzón Fm. The faults highlighted in yellow are measurements taken from the fault at Mesa Soledad.

Laboratory Results

Examination of thin section and sieved samples of lithified and unlithified material from Mesa Soledad yielded multiple varieties of benthic foraminifera after preparation and analysis in the lab (Table 2). The tests recovered from the sediments at Mesa Soledad were well-preserved across the facies they were found in. All foraminifera found are summarized in Table 2, with images in Figures 7 and 8.

Facies Code and Description	Features	Depositional Environment	Macro-Scale Bioclasts	Photo
F1: Muddy sandstone	Fine-grained sandstone with mudcracks	Lower-energy marine	None found	6B
F2: Fine-grained, fossiliferous sandstone	Poorly consolidated fine-grained sand; sub-angular grains	Nearshore	Gastropod and bivalve body fossils and casts	-
F3: Carbonate-rich, fine-grained, conglomeritic sandstone	Fossiliferous, extensive carbonate fabrics	Offshore	Bivalves, gastropods, bryozoans, shell fragments	-
F4: Coquina	Carbonate- and fossil-rich. Unit pinches out to the south	High-energy marine	Gastropods; body and casts and shell fragments	-
F5: Fossiliferous pebbly sandstone	Poorly consolidated fine-grained sand with sporadic pebbles; sub-angular to rounded grains	Nearshore	Gastropods; body and casts	-
F6: Pebbly sandstone	Poorly consolidated fine-grained sand with sporadic pebbles; sub-angular to rounded grains	Nearshore	None found	-
F7: Pebble bed	Well-sorted, well-rounded pebble bed	Nearshore/Beach	None found	6D
F8: Matrix-supported conglomerate	Well-rounded cobbles to medium sand, sub-rounded	Nearshore or Alluvial	None found	-
F9: Matrix-supported, angular conglomerate	Well-rounded to angular cobbles, tuffaceous matrix	High-energy fluvial	None found	-
F10: Clast-supported conglomerate	Well-rounded cobbles	Nearshore or Alluvial	None found	-
F11: Clast-supported glassy pebble conglomerate	Dark glassy pebbles embedded in fine-grained matrix-supported conglomerate	Nearshore or Alluvial	None found	6A
F12: Pumice-rich debris flow	Pebble- to cobble-sized pumice clasts intermixed with sub-rounded matrix-supported conglomerate	Nearshore or Alluvial	None found	-

Table 1: Generalized facies descriptions of the sediments found at Mesa Soledad. “F” standing for “facies”, with the numbers ascending roughly with grain size.

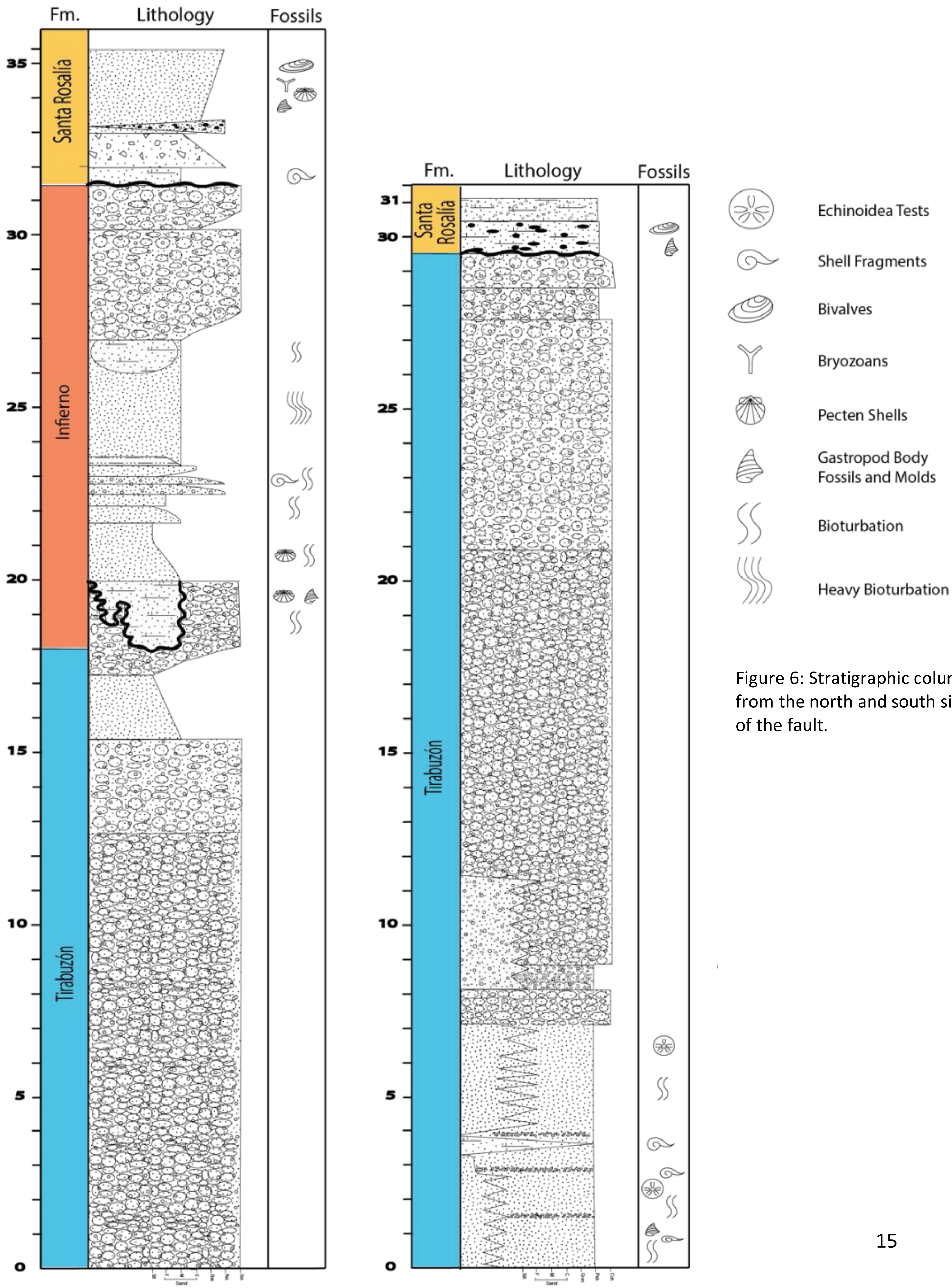

Figure 6: Stratigraphic columns from the north and south sides of the fault.

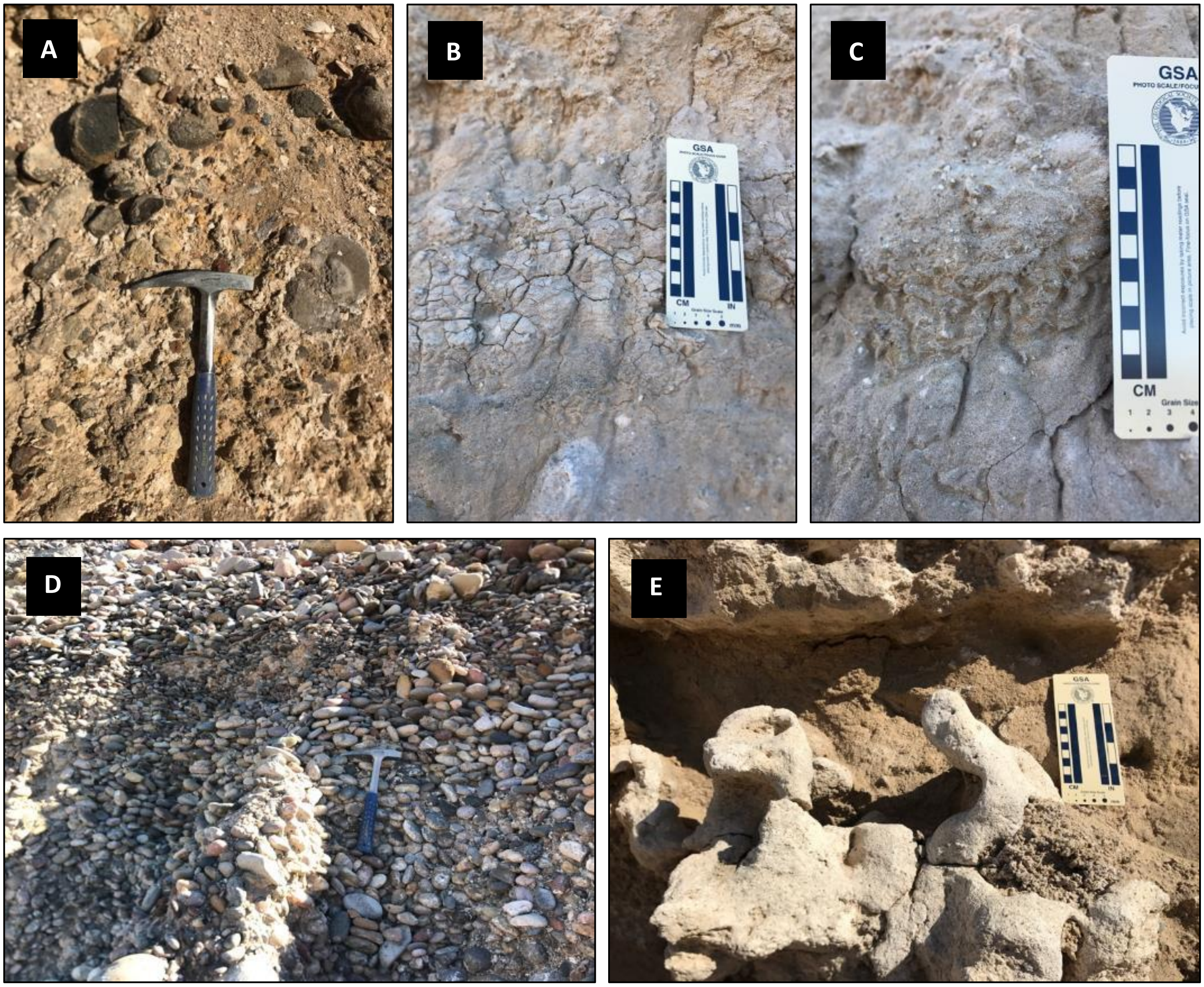

Figure 7: Outcrop-scale photos. A: Glassy, mafic clasts within the northern Santa Rosalia. B: Mud cracks in the Infierno Fm. C: burrows within the Infierno Fm. D: imbricated, well-sorted pebble bed in the southern Tirabuzón Fm. E: burrow casts from the Infierno Fm.

Figure 8: Macrofossils from Mesa Soledad. Left: Echinoid fossils found in the southern Tirabuzón Formation. Right: *Pecten* shells and barnacles from the Infierno Formation. Bottom scale in centimeters.

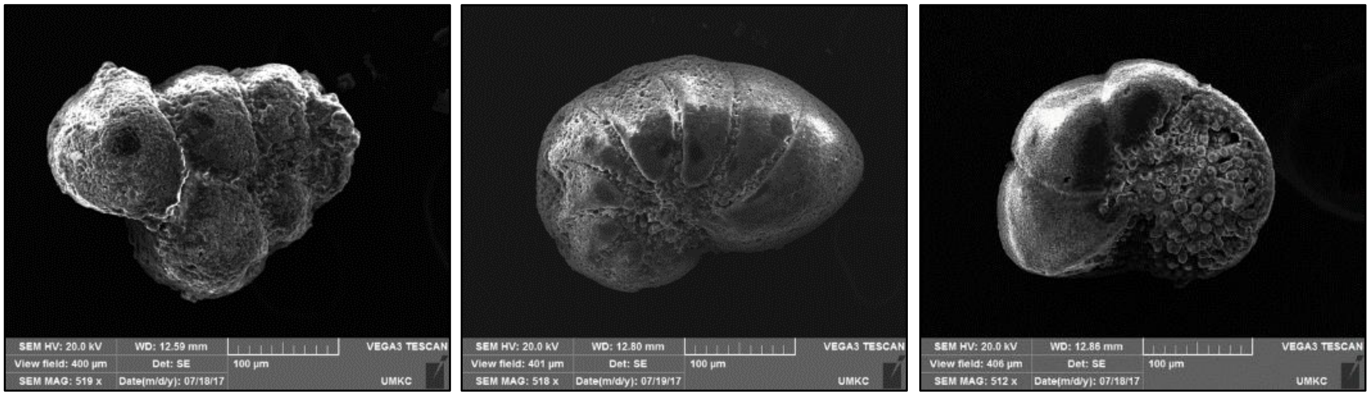

Figure 9: Images of benthic foraminifera from Mesa Soledad. Left: Globorotaliidae foraminifer from the Infierno Formation. Middle: Foraminifer from the Bolivinidae from the southern Tirabuzón Fm.. Right: *Ammonia* foraminifer under SEM from the Infierno Fm. All images taken with a scanning electron microscope.

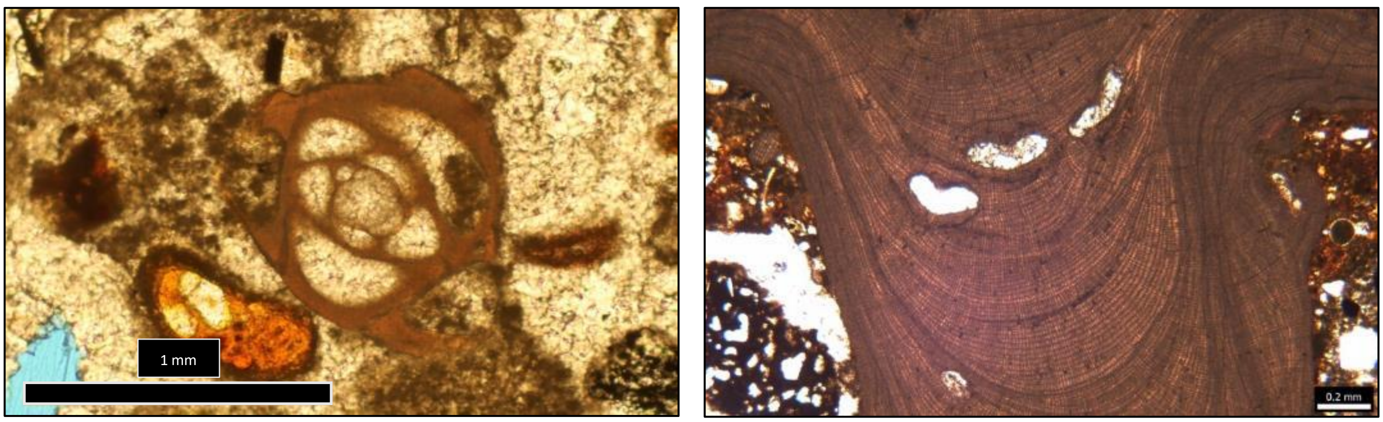

Figure 10: Fossils in thin-section. Left: Globorotaliidae foraminifer from the northern Santa Rosalía Fm. Right: Algal structure also from the northern Santa Rosalía Fm.

South	Santa Rosalía	Globorotaliidae
	Tirabuzón	Bolivinitidae, Globorotaliidae
North	Santa Rosalía	Globorotaliidae, Spiroloculinidae
	Infierno	*Ammonia*, Globorotaliidae, Bolivintidae
	Tirabuzón	None found

Table 2: Benthic foraminifers found within each formation on either side of the fault.

DISCUSSION

With the information gained from studying the exposures at Mesa Soledad, it is possible to draw conclusions in two different respects: classifying depositional environments and the syntectonic depositional history. The facies descriptions along with the fossils acquired help us work towards a simple, inferred sea level curve, creating a more robust description of the depositional history, especially in regard to potential paleoenvironments. Creating a sequence of events for the syntectonic deposition of the three formations helps to create a higher-resolution snapshot of how the Santa Rosalía basin may have been deforming during this Plio-Quaternary time.

CLASSIFICATION OF DEPOSITIONAL ENVIRONMENTS

It is inferred that the short-system processes dominate at Mesa Soledad, putting the basin close to the sediment supply (Figure 11). The sediments found are largely reworked material from the shore, possibly supplied by a coarse-grained delta. In addition, there are some instances of tuffaceous material occurring in the matrix of conglomerates, from local volcanic activity at the time of deposition.

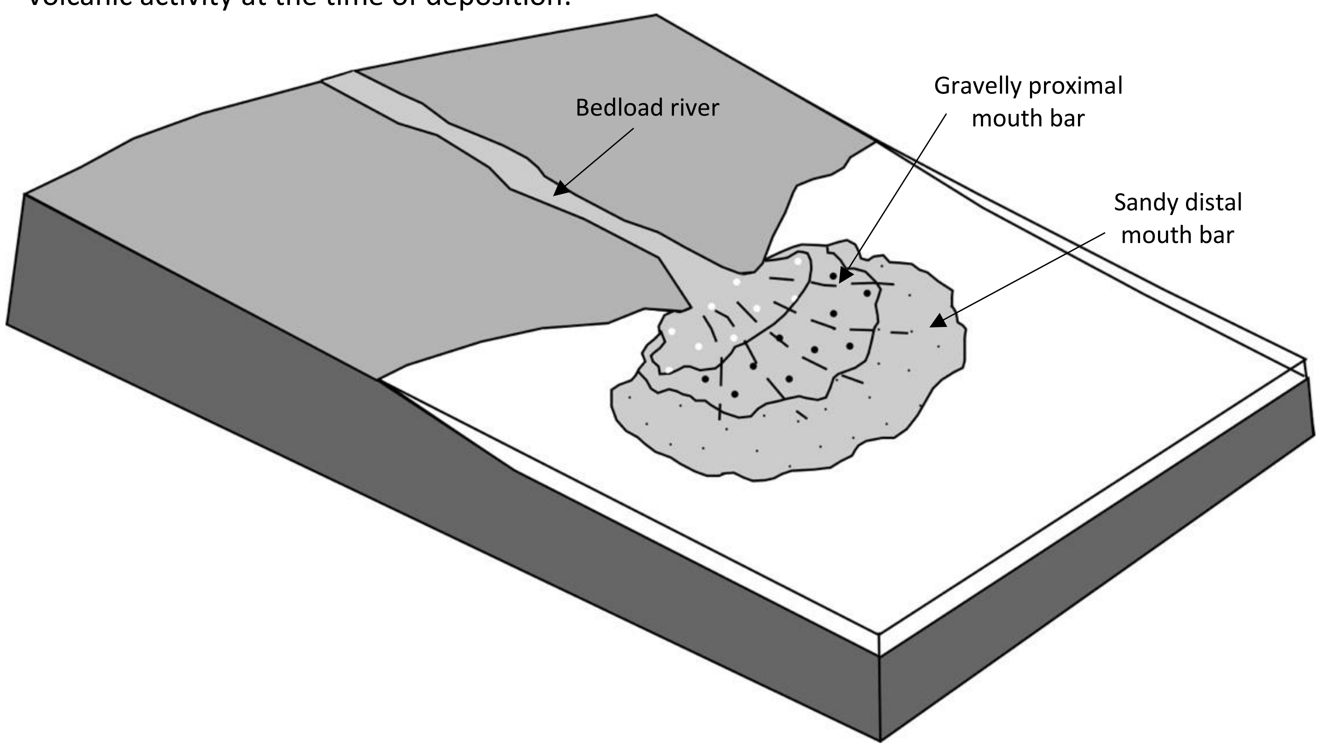

Figure 11: Coarse-grained delta block model adapted from Nichols, 2009.

There is an overall pattern of regression within each of the three formations present at Mesa Soledad, with a disconformity separating each unit (Figure 12). At the base of the

Tirabuzón Formation on the southern half of the outcrop lies a fossiliferous sandstone with a lag deposit of echinoid tests 2.3 m from the base of the section (F2). This suggests a higher energy, offshore environment that then transitioned up into a relatively deeper, higher-energy environment, allowing for the deposition and formation of a coquina facies, with another F2 facies lying above it. The formation of the coquina between these two sandstone facies may correspond with a substantial decrease in siliciclastic sediment supply, allowing for the carbonate-rich facies of the coquina to form. Laterally to the south these units gradually transition to a pebbly, less fossil-abundant sandstone (F5), notably lacking echinoid tests but still maintaining other fossils such as gastropod casts and shell fragments, suggesting a foreshore environment. The extremely well-sorted cobble and pebble beds above indicate a high-energy beach or fluvial setting given the clast-supported nature of the bed. The F5 just north of the pebble bed and the first 3.5 m of the overlying conglomerate laterally grades into the aforementioned units, in a way similar to the echinoid-rich sandstones in lower units, which also exhibited lateral grading from one facies description into another. This beach or fluvial environment transitions up into a more definite fluvial setting with the clast- and matrix-supported conglomerate, with an abrupt sand facies below the disconformity with the Infierno Formation. This facies suggests a sharp rise in sea level, allowing for a sandstone to be in bounded by two F10 facies within the same formation.

The base of the Infierno formation at this exposure indicates a deeper offshore environment, supported by the carbonaceous nature of the facies and the foraminifera, body, and trace fossils found within, including numerous benthic foraminifera, echinoid fragments, barnacles and various bivalves and gastropods. An F2 rests above this fossiliferous facies, with preserved burrows and a high density of *Patinopecten* shells, which favored a low-level epifaunal habitat (PBDB). This high concentration of *Patinopecten* shells could be considered a lag deposit, indicating a higher-energy offshore environment. It is worth noting that filter feeders like *Patinopecten* could not have thrived in an environment with a high sediment deposition rate. This helps to further constrict the potential paleoenvironment in regards to sediment supply. More F2 units, still containing burrows, though lacking *Patinopectens*, support a nearshore environment, moving up to F5, then back to more F2 facies until a lens of calcareous and bioturbated sandstone is encountered, suggesting a deeper depositional environment. This then transitions into a subaerial environment, indicated by the poorly-sorted conglomerates found up until the disconformity with the Santa Rosalía Formation.

There are two identified facies of conglomerate near the top of the southern section, underlying the Santa Rosalía Formation, that could either be considered a further continuation of the underlying Tirabuzón, or a remnant of the Infierno Formation. Reasons being the facies' compositions suggest a subaerial environment, an environment found both at the upper boundary of both formations. The poorly-sorted clasts are void of any fossil material, and also have orange staining (possibly from oxidation) and weathering rings around many of the larger clasts, further suggesting a subaerial environment (F9). Their tuffaceous matrices suggest they were deposited during a time of volcanic activity while being relatively near the sediment source.

The Santa Rosalía formation is the only unit present at Mesa Soledad that remains undisturbed by the faulting event. Its base, a coquina facies (F4), was deposited in an offshore, high-energy environment. The well-rounded, mafic pebbles contained within this F4 suggest this was deposited close to a volcanic eruption. Then, it transitions up into a conglomeritic sandstone which lacks macrofossils but hosts several benthic foraminifera, indicating an offshore-foreshore transition zone. Even further up section, another F4 is found, indicating another high-energy, offshore environment. A pumice-rich debris flow (F12) lies above. This facies doesn't suggest a specific marine environment (e.g., nearshore, beach, offshore, etc.), but it does suggest close proximity to another volcanic source. An F11 lies above, further suggesting close proximity to a volcano. Finally, another F3 is present, with the most diversity in macrofossils found in the whole section, including, bivalves, bryozoans, gastropods, limpets, and barnacles. Benthic foraminifera were also in

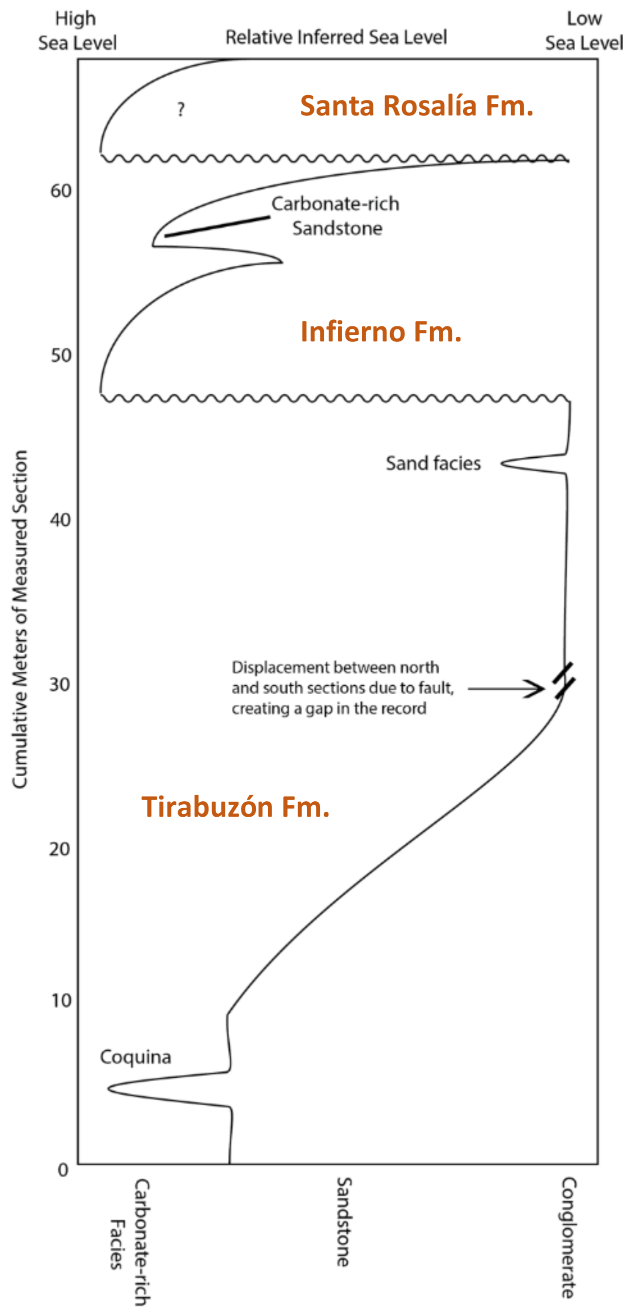

Figure 12: Idealized sea level curve at Mesa Soledad. The vertical axis represents meters of section measured. The zero value represents the stratigraphic bottom of the Mesa, south of the fault, continuing up to the northern Tirabuzón, indicated by the arrow.

this facies, supporting another offshore environment.

This pattern of marine regression throughout the Tirabuzón and Infierno Formations is similar to what's described by Wilson and Rocha (1955). However, the amount of the Santa Rosalía formation that is present at Mesa Soledad is not complete enough to glean a true pattern from the present lines of evidence. Also, the sometimes-sudden changes in facies composition could be related to sediment supply rates, especially in relation to the formation of coquina facies.

SYNTECTONIC DEPOSITIONAL HISTORY

Stratigraphic and petrographic analyses of Mesa Soledad's formations provide insight as to how tectonic events have affected the deposition of the Santa Rosalia basin's youngest units. Wilson and Rocha (1955) noted the occasional absence of the Infierno throughout the basin, resulting in the Santa Rosalia lying directly above the Tirabuzón, similar to what is seen south of the fault at Mesa Soledad. At this particular outcrop, we believe the absence of the Infierno is a result of one of two things: 1) The fault's dip-slip component uplifted both the Tirabuzón and the Infierno formations, causing the southern Infierno to erode unevenly in comparison to the deposits on the northern side of the fault (Figure 13). 2) The ancient sea level that deposited the Infierno was high enough to deposit above the Tirabuzón's fluvial deposits in one region of the basin, but not high enough to deposit on the marine facies in another location. Post-deposition, the faulting event caused lateral as well as vertical displacement, placing the fluvial deposits and the overlying Infierno deposits next to the marine deposits. However, it is most probable that #1 is the case for Mesa Soledad, considering the lateral component of the fault is unknown.

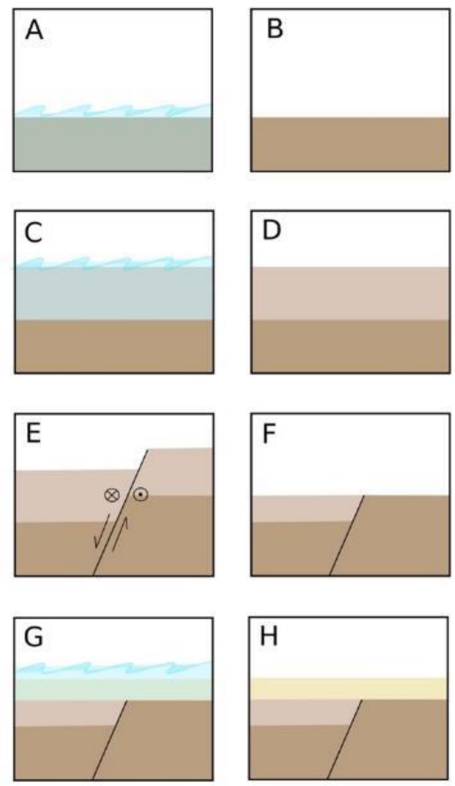

Figure 13: Cartoon timeline of the syntectonic depositional history at Mesa Soledad. A: deposition of the Tirabuzón Formation. B: Tirabuzón after regression. C: Deposition of the Infierno Formation. D. Infierno Fm. after regression. E. Uplift event with vertical and lateral displacement. F: Erosion of the Infierno, effectively removing it from the southern side of the fault. G: Deposition of the Santa Rosalía formation. H: Final formation at Mesa Soledad after erosion and uplift.

If continued, this research would benefit from determining the lateral component of the faulting event, as well as a more robust analysis of grain sizes from the different facies present at the outcrop. This could help define even more specific depositional environments, creating a more accurate sea level curve.

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