2. GEOLOGY

Geology is the science of dealing with the dynamics and physical history of the Earth, its rocks and the physical, chemical, and biological changes it undergoes. The Tijuana River Estuary -- where the Tijuana River meets the Pacific Ocean - is an ever-altering region, carved from Earth by geophysical events. The ages have made it a "middle ground," semi-enclosed between land and sea. Lush with productive plants, it is a sanctuary for birds, crustaceans, fish and insects. It reminds us of prehistory when plants and animals began to thrive out of water, because it contains both aquatic and terrestrial species, as well as fresh-water and salt-water species. They adapted to Earth's long-term transformations and survive short-term geological changes. Two children, Justine and Marc, became involved in investigating the geology, when a mini-geological event impacted their yard not far from the estuary.

Justine Iver's little brother, Marc, was crazy about playing in his box of dirt and sand behind their house in Imperial Beach, California. He had created a prehistoric world of make believe using toys and construction materials that the Ivers called "Marc's zone." It was near a vacant lot owned by the neighbors, Mr. and Mrs. Chamorro. When a bulldozer began moving dirt around on the lot, Marc nearly went into a trance watching it. That was until a pipe cracked and spewed water out over the exposed dirt.

The Iver family awakened on a Saturday to find that a portion of the Chamorros' lot had slipped down into their own, collapsing Marc's zone and its elaborate system of miniature canyons. Justine, in a rare moment of sisterly concern, went out to survey the disaster with Marc, who was beside himself with tears.

"I think, Marc-bo," she said, with her arm around his shoulder, "that this is a micro example of what my science teacher would

call the *geomorphic process*. That's the process that shapes the Earth.

"Morph?" Marc asked, sniveling, "like my dinosaurs that morph into trucks?"

"Sort of. But in this case, it's the Earth transforming, not toys. Morph means form. Geo means *Earth*."

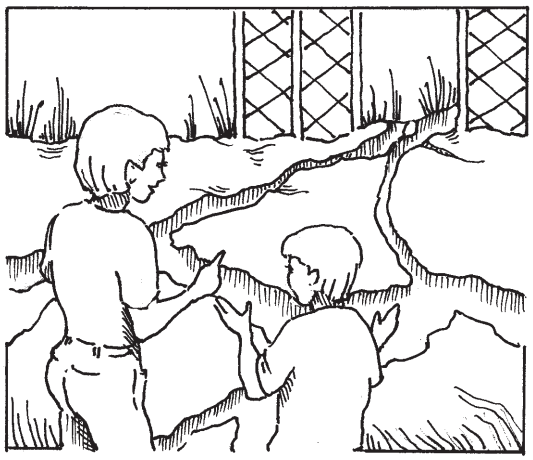
"Well, whatever it is, it's terrible!" Marc declared, shoving a partially buried strip of wood, he added with rising panic, "Where am I going to play!"

Watersheds and Drainages

Justine surveyed the damage more carefully. "Your sandbox seems to be the termination for this particular watershed."

"Justine. Speak English! You sound like sci-fi. What's a watershed?"

"An area where water sheds. The water in a watershed is both *surface runoff* and water that sinks in. The water that sinks in is called *infiltration.* A *watershed* is the land where surface runoff begins, then drains. Might be into a stream, a lake, a reservoir, or any other body of water. A watershed is also called a *drainage basin*. The neighbor's property there is a high point," said Justine pointing up at the Chamorros' hill of upturned earth.



"And surface runoff is what wrecked my zone?"

"Yeah." Normally, Marc wasn't a particular priority, but her interest in geology inspired her to make an exception. "Much of the water came here, pulled by gravity. That's a force within Earth that attracts objects downward. Some probably went off in another direction. There," she said pointing up the small hill. "At the top, where the water began traveling down is a *drainage divide*."

"I can still see the little trails…the places where the water wiggled down," Marc commented, looking at the rivulets, the miniature streams carved in the soil.

"That's right, Marc-bo. Those would be creeks and rivers in a bigger scenario. Look at the little round spots, where the water pooled up before continuing. Basically, those are like lakes, or the reservoirs behind dams. Also, there are probably underground *aquifers* we can't see. Aquifers are rocks that have spaces in between that contain water, like…you know…underground creeks and lakes. "

"Does *all* the water come down?"

"No. Some of the water also soaked into the Chamorros' lot. More would've stayed up there, if the land hadn't been graded. Plants would've slowed the water down and held it underground, in and beneath the roots. Anyway, some water soaked in, going down until it hit hardpan, a firm layer. The water that accumulates under the ground is called *groundwater*."

"Then what's it called when it gets down to the flat part? Here," he said pointing at his feet.

"You, Marc, are standing in the marsh area, a low flatland. It's like the Tijuana Estuary. You know how flat it is there. And it's suffering from sediment -- deposits of

soil carried by running water -- just like in your Zone here."

"Yeah," Marc reflected, temporarily soothed by the thought that his disaster had something in common with the nearby reserve. "I really like the estuary. Where does its water come from?"

Justine gestured off to the south and eastern horizon. "See those mountains past Tijuana?"

Tijuana River Estuary's Most Common Natural Drainages

Tijuana River	Las Palmas
Upper Cottonwood Creek	Rio Seco
Lower Cottonwood Creek	La Cienega
Pine Valley	Las Calabazas
El Flondo	Las Canoas
Campo Creek	El Beltran

The slate-blue horizon was jagged with mesas and peaks as high as 6,000 feet. The family had hiked in the forests of juniper, oak, mountain mahogany and pine. The Tijuana Estuary drainage is 1,750 square miles, one-third in the United States and two-thirds south of the border, in Mexico. There can be as few as one or as many as hundreds of *sub-basins* or *catchment* areas that hold water. "That's called the Peninsular Mountain Range," she explained "One drainage to the Tijuana River comes from all the way up there. There are dams too. Barrett Dam and Lake Morena Dam are in San Diego County. Rodriguez Dam is in Mexico."

It was a bit too much information for a five-year old. "*Just-teeeen*! You always think you know everything. Who cares? I just want to play!" Marc plopped down in the mess and recommenced crying.

"Get a grip, Marc, it's not the end of the world." She'd thought about going to the mall with some friends, but looking down at her brother in the upheaval, Justine got another idea. "How about making a model of a place we know? Like the estuary? The Chamorros' property could represent the Peninsular Mountain Range."

Marc looked up at her skeptically.

Justine was thinking fast, considering how to apply the stuff she'd been studying in geology to their backyard, and cheer up her brother. "A model of the way land moves around *over millions of years*."

"Millions of years" reminded Marc of his dinosaurs, reminded him of fun. But he was still dubious. "What would we have to do?"

"Well, we'd need to build an ocean. The soil is wet now. Digging a big pit'll be easy. Maybe we can get Dad to help, just to get us going. I think we should start in the Ice Age, the Pleistocene Epoch, from 1.8 million years ago until about 10,000 years ago."

"Were dinosaurs here then?"

"No, but there were giant camels, horses, deer, dire wolves, and pig relatives called peccaries. There were also gomphotheres, prehistoric cousins of elephants."

"Great!"

"This is going to be awesome, Marc-bo.

You'll see," she said encouragingly. "Did you know the ocean was 400 feet shallower during the Ice Age, and the shoreline was miles out? You know how close we are to the beach now? Our house would've been miles farther away.

"But there weren't people then, were there?"

"Yes there were, but not very many and they were really spread out. There were mastodons and Columbian and Imperial Mammoths. I've heard there were at least 17 different species of sharks and rays, including the great white shark. And giant ground sloths and maybe a few saber-toothed cats." "Mmmm…saber-toothed cats," Marc considered, nibbling his finger.

"Why was the ocean so far away?"

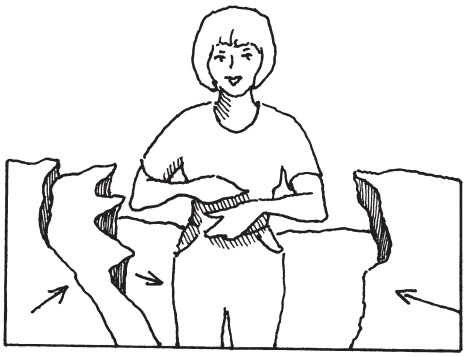
"Same reason global sea level rises and lowers. Glaciers advancing. Glaciers retreating. Because much of the northern and southern parts of the planet were frozen, covered with ice, keeping the liquid water level lower. Let's get digging. I'll see if Dad can help."

Dramatic Land Formations

Earth formed 4.6 billion years ago, according to scientists' best estimates. It took 400 million more years for a crust to form. Obviously, these are long-term changes, when one considers humans have been around for only about four million years, 1/1,000 (or .001) of the total history of the Earth.

Fortunately, the kids were working on a much smaller scale, both in terms of time and space. With Dad's muscle at work, ocean building went pretty quickly. The hole he dug was about four by four feet, and around a foot deep. While their father worked, he explained that continents used to be joined as one super-continent, called *Pangaea*. Two hundred million years ago, blasted apart by rising heat from the Earth's interior, land masses began moving in opposite directions. The climate changed and mountains formed. North and South America are still moving west. The rest of the continents are headed east. Since continents are moving approximately 20 centimeters every year, that amounts to 32 miles in a million years, Dad explained. The Pacific Ocean is shrinking while the Atlantic Ocean is growing.

"I wanted to explain to Marc how land changes from instability beneath the Earth's surface," Justine commented, self-importantly. "Huge slabs of crust that move around are called tectonic plates. These plates explain the movement of continental masses. That's part of what makes the Americas move west, right, Dad?"



"Right. All this movement started long before the Ice Age, in the early Cenozoic Period…"

"I forget when that was." Justine admitted.

"The Cenozoic began 65 million years ago. In our region, the changes are all about rising and falling sea levels. Just in the last 2.67 million years, sea level has risen and fallen up to 625 feet. We can read San Diego's topography like a chronicle of those changes." Then Dad said, "Think about different kinds of land you've seen here."

"I know that when the ocean was higher, waves broke away at rocks to create sea floor, and eroded rocks to form beach

cliffs."

"How about the mesas and terraces," Dad continued. "How did they get so flat?"

"I'll bet they were on the bottom of the sea!" Marc yelped.

"Good Marc," Justine praised. "They're at different elevations because they formed at different times when the ocean was at different levels,"

"Here in San Diego, around 125,000 years ago *tectonic uplift*, that's Earth's crust's structure uplifting, thrust what had been undersea flat places above water level. That pushed water back off the land." Dad gestured eastward toward the Chamorros' yard. "What is now the Tijuana River cut through these raised surfaces for almost 80 miles, delivering water to the ocean. Plus, as the northern glaciers melted, the sea level rose making the estuary more viable. In other words, estuarine plants and animals could live there. There was more relatively flat land that was sometimes filled with salty water, sometimes with fresh water."

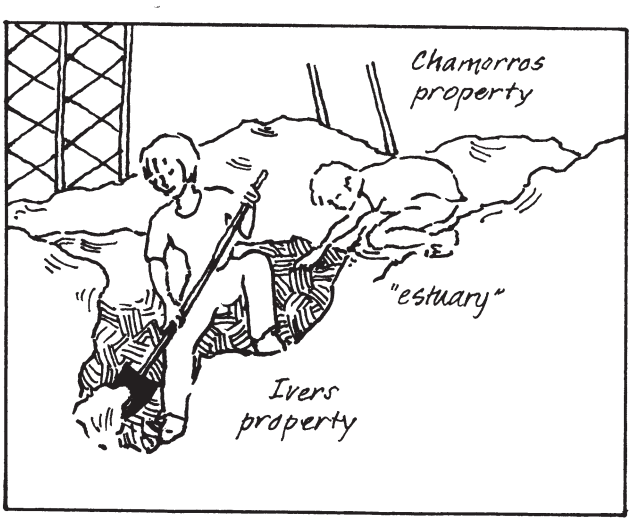
Marc looked worried. "Is the water still rising?"

"Sea level still rises but very slowly. If you live another 95 years, the mean high tide will be about 7 1/2 inches higher than it is now. You can probably handle it."

"At school we learned that the average depth of the ocean is around 2.2 miles," Justine blurted, as she stood by looking into Dad's hole. "Of course, there are a lot of features underwater too - volcanoes, mountains and valleys."

"Yes, and you could be installing the topography. And don't forget the big canyon offshore San Diego," Dad pointed out. "It's a trench where the ocean floor really drops off, almost a mile deeper."

"Let's make that!" expressed Marc. He passed Justine a shovel and nudged her down in the pit.



"Watch it, Marc! Why don't you move up there to help with the continental shelf?" "What's a continental help?"

"*Continental shelf*," corrected Dad, flattening dirt around the edges of the hole. "It's sort of an apron around the continents, like this, before the ocean really drops off to deeper depths. The shelf is about 400 feet deep in most places. But you can't fill the ocean over the shelf yet, guys. There wasn't a continental shelf then. The four hundred feet was above sea level, because so much of Earth's water was trapped in glaciers."

Then he suggested that, to retain the water, they line their "Pacific Ocean" with plastic. "And I'd put plastic under the whole model. Otherwise the water won't stay there very long. The liner can represent *limestone*. That's a class of sedimentary rock.

"Yeah, Marc, you'd love limestone. It's full of fossils."

"The limestone? Or the plastic?" Marc puzzled.

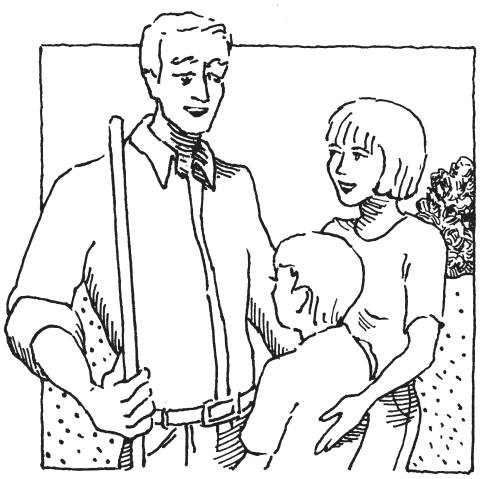
Dad laughed. "Both! Limestone is made up of calcium carbonate, much of it fossil fragments from animals that lived in the ancient, shallow oceans. Some of the famous dinosaur bones have been discovered in sedimentary rock." And plastic is made out of petrochemicals, oil taken from deep within the Earth, often from under the ocean. You see, petroleum, like coal, is a biological product. It is the organic debris of former life, buried, transformed, and preserved in sediments.

Justine and Marc nodded, continued their work. Their dad inserted a big sheet of plastic and dragged over the hose. In no time, they had the "ocean" filled with water. The three stood by, admiring their handmade waterscape.

There was a significant problem though. "How's the water going to get outside the hole, so we'll have an estuary?" Marc asked.

The Role of Weather

"How about weather?" Dad said. Their father was a meteorologist and more curious about barometric pressure than about what was for dinner. For him, thinking about weather was as easy as breathing. "Weather already changed your installation here, Marc."



Marc didn't get the connection. "Weather didn't change it. The Chamorros' pipe did." "The broken pipe created "rain" and rain created flooding and erosion." Dad smiled. Justine quickly intervened. She didn't want Marc to collapse into tears again. "Okay, Dad, but what about the weather? What does it have to do with the way the land changes?"

"Weather is created by global wind circulation patterns, which also drive the ocean water circulation. And as a consequence, there are storm systems. You can see for yourselves, down at the estuary, how forceful currents and storms breakdown and remake the dunes and the intertidal channels - how erosion leads to sediment build up and flooding leads to scouring. It's changing all the time, mostly due to wind, ocean water circulation and currents."
"I never thought of it on that level, Dad," admitted Justine.

"Well, I don't even understand what you're talking about," Marc pouted. "What would be really cool is if Dad would let us bring the fan outside, to make wind."

"You could probably talk me into it, for the sake of science, but I can't imagine the idea making it past your mother. How about taking Marc to the slough instead, Justine?" their father suggested. "Sort of a fact-finding mission."

"It'd probably give us a better idea of how to build the land part of our model," Justine admitted. "We'd better take some paper and pencils so we can take notes. Maybe the Reserve staff will give us a map, too."

Land Alterations

As they parked outside the Visitor Center, Justine pointed to the west. Marc, the *sand dunes* are between us and the ocean. We'll have to add those. They create a sort of lip, keeping the salt water inland longer.

Types of Estuaries

Coastal plains estuaries – river valleys which were flooded with sea water when the sea level rose after the Ice Age.

Tectonic estuaries – estuaries formed by shifting land forms, such as slipping along a fault line.

Bar-built estuaries – the mouths of large rivers where sand and/or mud sediment builds up across the mouth.

Fjords – estuaries with deep sides carved out by glaciers.

ESTUARIES MAY BE OF MORE THAN ONE TYPE

Estuary Basin Types

- Long, narrow tidal river
- Coastal area protected by a barrier island or reef
- Embayment with narrow , restrict outlet to sea

Tijuana River Estuary is an embayment.

Sand dunes are one of the defining characteristics of any estuary, if it's quasi-enclosed."

"Where does the sand come from?"

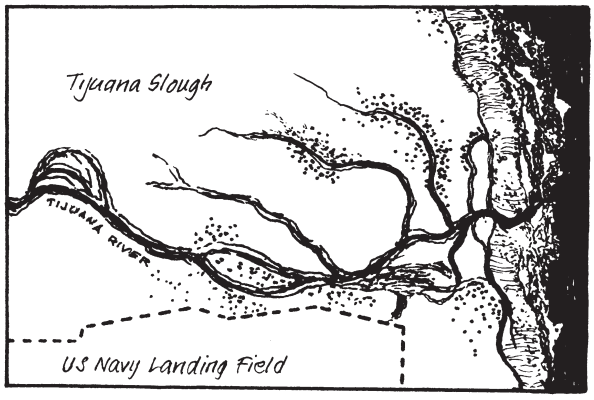
"It washes down the watershed into the Tijuana River and flows out to the ocean. The problem is that there are so many dams now restricting water flow, that the grains of sand and other sediment rarely get to the beach. Another problem, *if* these grains get to the beach, is that they'll get washed away in high tides and be lost forever in the offshore trenches…like the submarine canyon we excavated for our model back home. The worst part is that some developers tore down these dunes in order to build houses along the beach; that action really leaves the estuary vulnerable."

"Humans can sure do awful things."

"Well, we're trying to get better. That's why it's good to learn this stuff about the estuary. Once the sand is there, ocean currents and waves move sand along the coast, just like Dad explained. The sand movement is called *littoral drift.*"

"There you go again…*Justine, the Science Queen*," her little brother said, rolling his eyes.

As they walked into the Visitor Center, Justine kept talking. "Storm waves move sand into the estuary, and that can block the entrance. The *ebb tide*, the water moving out of the estuary, has to be strong enough to scour and clear this accumulated sand. Otherwise the channel will close



off and fill from the sediments carried down by the river." There was plenty to look at in the Center. Marc was pretty distracted.

To get his attention, Justine pointed to the aerial photograph. "See these *intertidal channels*? It takes powerful currents to shape the estuary channels and shoreline. The currents distribute *sediments* that roll down from drainages throughout the estuary. Fine particles wash out with the tide. Heavier particles settle and resettle."

"What's a sentiment?"

"Sediment. Partially, it's particles broken or worn off rocks. Newly created mineral matter is mixed in, small stuff from chemical

solutions or from organic activity. The particles can be big, medium and little grains."

"Doesn't the estuary eventually fill up with sentiment?" asked Marc, still mispronouncing.

"Well, that's what happens.The Tijuana Estuary has major problems because *sed-i-ment* is not being scoured now, because the river is so controlled. Much of its force and power have been reduced."

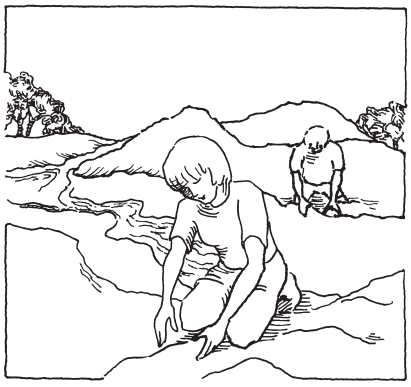
"So the estuary has less water in it?"

"Yeah and if enough sediment moves in there, it might turn into solid land. The estuary - the delta where the river meets the ocean - would be gone." Sediment deposits change the elevation and this allows different plants to grow, like pickleweed, which doesn't grow in water."

"Then what happens when a pipe breaks like in our model, or when it storms?" asked Marc. "When it rains hard, does the sediment all wash away? Like it carried away the canyons I made?"

"Well, not all of the sediment. At least, hopefully not. But the scouring that occurs during flooding creates an environment for other plants, like cordgrass, because it grows in the water."

"Let's go home and make dunes and channels," said Marc. "There's plenty of sand there."



Back in the yard, Justine and Marc had no problem making little channels along the edge of their "ocean" closest to the Chamorros' on the east. They also created some model-sized mountains, hills and mesas.

"How are we going to get the water to come up onto the estuary part?" Marc wanted to know.

"How about putting ice everywhere?"
"Yeah!" squealed Marc. "It'll be like melting glaciers."

They again consulted with their father inside, who dampened their enthusiasm with the news that the continental glaciers did not extend down to San Diego. "You two might want to think about the trends that signaled an end to the Pleistocene."

"Dad, you're just trying to get us to think about weather. Typical."

"I'm sick of all this talk!" Marc was impatient to get the delta between the hole and the "mountains" on the Chamorro side wet, so it would be more like an estuary.

"During the Ice Age, there weren't glaciers covering San Diego," their dad reported. "It was wetter and cooler though, more like Oregon and Washington are now."

"Remember how much it rained in Seattle when we visited, Marc?" Justine asked her little brother. "Like that."

"Well, then we need a lot of rain," Marc pointed out.

"How about rain on the mountains then, that "Peninsular Range" up toward the Chamorros' lot?" Dad suggested. "You can make rain with the sprinklers."

"Good thinking, Dad," added Justine, grabbing Marc by the shoulder and heading outside again.

Modern Weather

The children knew, and their father had many times explained, that today San Diego's coastal region has very mild weather. Three-quarters of the days are sunny and the temperature averages 76 degrees. Winds are usually offshore, westerly or southwesterly, meaning that they're coming off the land.

"Our region is drier than most, Marc," Justine pointed out as she turned on the sprinkler. "Remember the photo of earlier times down at the estuary. There was a landlocked pond at the north end a hundred years ago. And the river had a second mouth, south close to the bullring in Mexico. Those aren't there any more."

"Where did all the water go?"

"Damming keeps much of the water upstream, storing it for human use.

"We don't have any dams in our model, do we?"

"No. Also, now the Tijuana sewage treatment plant delivers treated sewage directly out into the ocean, skipping the estuary, which is good because we don't want the sewage in here."

"And we don't have a sewage treatment plant in our model either. So why isn't the estuary filling up? What about the weather?" Their pseudo-ocean didn't exactly seem to be overflowing.

"Maybe the wetness here is making the land cooler, creating a coastal fog, too small for us to see," pondered Justine, feeling near the soil. "Some coastal fog, generated by water that is colder than the air, cools things off."

"Cooling isn't going to make an estuary, Justine," Marc pointed out.

"That's right, but weather would." Dad had just showed up, carrying the fan, on a long extension cord. He positioned it at a distance from the ocean side, facing toward the mini mountains. "Now, listen. Keep this away from the water. Water and electricity are what lightning is all about. I don't want either of you to get zapped. No bolts or jolts required, got it?"

"Duh, Dad," Justine remarked. Marc, by now a miniature authority, nodded in agreement.

"Averaged out, San Diego has ten to twelve rainstorms a year. Spread over twelve months, that's very few and some years there aren't any. Meteorologists like to get average figures, but the truth is San Diego is given to extremes. San Diego usually has long, dry spells, with hardly any rain. Drought depletes the groundwater supply and dries out land and vegetation with it."

"Oh, no!" Marc squealed in frustration. "Now you're talking about dry spells!"

"But every two to seven years, El Niño acts up and we get deluge after deluge."

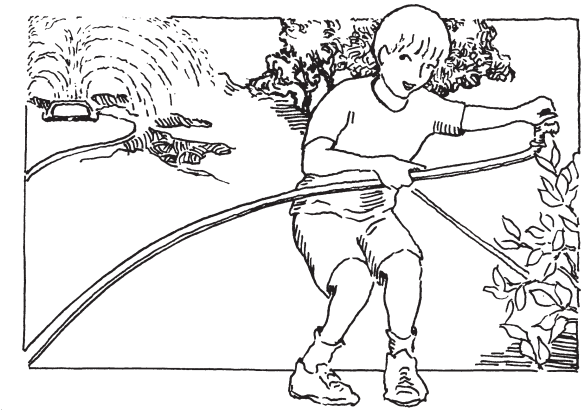
"El Niño? What's that?"

"It's instability in the air and sea that leads to unusually warm ocean water."

"It generates fierce storm systems," Justine added.

"What does El Niño do to the estuary?" Marc wondered.

"Flooding. In some ways flooding is good because it recharges water systems. It also flushes the drainages of sediment." Marc stuck his finger in the black plastic-lined ocean. "This water is getting really warm. Maybe El Niño will come here. I'm going to turn up the sprinkler," he announced with finality, scrambling off.



Justine and Dad laughed. Dad turned on the fan and Marc turned the sprinkler on full blast to simulate an El Niño. Marc watched his transformed zone carefully, as the model melted into contemporary times. Water seeped into the estuary from the Chamorros' mountains. The fan blew miniature waves toward the model dunes. If the "storm" continued, the model estuary would demonstrate that real estuarine geology is always changing.