Suspect Terranes and Continental Growth

The dissection of western North America is forcing geologists to decide exactly what they know about the travels of continental rocks

I wouldn't have seen it if I hadn't believed it.—OLD GEOLOGIST'S SAYING

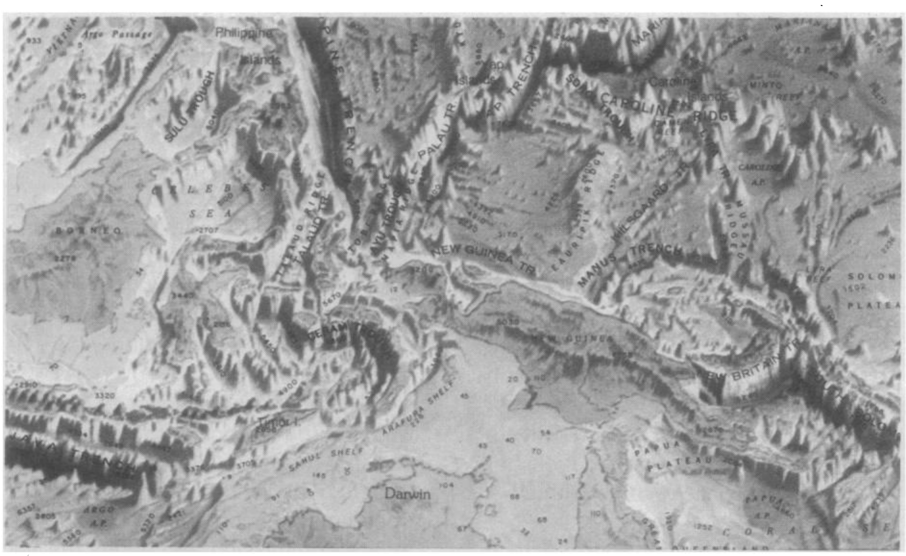
Continents do not change in a geologist's lifetime, but perceptions of them do. Conceived in studies of the ocean crust, plate tectonics depicted ocean crust plunging beneath the continental edge and creating great chains of volcanoes. Continents would collide and throw up new mountain ranges. Thus the continents would grow. After 10 years, some geologists are deciding that this new view of continents is too simple, that it will never fit the real rocks.

The difficulties with the simplistic application of plate tectonics to the continents began with the realization that at least a few parts of western North America had been rafted from distant sources and plastered against the edge of the continent (*Science*, 7 March 1980, p. 1059). That has prompted some geologists to forsake the broad-brush, plate-tectonics picture of continents and their growth. In its stead, they are busy carving the borders of the continents into hundreds of pieces called tectonostratigraphic terranes (a spelling chosen for this special use of the term terrain). This is the only way, they say, that geologists can begin to deal with the great complexity of continental relative to marine geology. Only after individual terranes are better described, they say, can geologists paint a broad picture of how the continents came to be the way they are. When geologists take the terrane approach, say these terrane analysts, they will find that most of the continents came as bits and pieces from the sea.

When about 100 terrane enthusiasts gathered at Stanford University at the end of August,* the first order of business was to map the terranes around the edge of the Pacific Ocean. The centerpiece of the meeting was the circum-Pacific terrane map† prepared by David Howell, Elizabeth Schermer, and David Jones of the U.S. Geological Survey (USGS) in Menlo Park, California, Zvi Ben-Avraham of Stanford, and Erwin Scheibner of the Geological Survey of New South Wales, Australia. They have divided the Pacific borderlands into more than 300 different terranes. They carved the western United States into 46 terranes, the far northeastern Soviet Union into 32 terranes, China and Mongolia into 49 terranes, and the Philippines into 9 terranes.

There is not that much new about the lines that these terrane mapmakers have drawn. Most of the boundaries can be found on standard geologic maps that locate differing rock types. On the terrane map the lines take on the additional job of separating rocks that have no proven geologic connection with their neighbors. A much discussed example at the meeting was the 500-kilometer-long slice of central California called the Salinian terrane. Above sea level, it extends from just west of San Francisco Bay, a few kilometers west of the meeting room, inland to just south of Bakersfield at the end of the Great Valley.

Salinia had for 30 years seemed odd and out of place. Underlain by granite, it is surrounded by a jumble of altered marine rocks called mélange. According to the plate-tectonic scheme, granite forms inland from the zone where an oceanic plate sinks beneath the edge of a continental plate. Angling into the mantle beneath the continent, it partially melts, producing magma that rises to form granites and their overlying volcanoes. This volcanic arc would thus be farther inland than its erosional debris collecting along the shore and farther still from the creation of mélange by the subducting ocean crust. Surrounded by mélange and bounded by faults, such as the San Andreas on the northeast, Salinia did not seem to have formed where it is today. By present-day definitions, it would have been called a suspect terrane, as most of the rocks within an



The mayhem of plate tectonics in the southwest Pacific

Eli Silver and Randall Smith of the University of California at Santa Cruz have proposed that today's southwest Pacific can serve as an analog of the interaction of ocean and continental plates that accreted terranes to western North America before 65 million years ago (Geology, *April 1983, p. 198). As North America did then, the Australian continent is plowing into an oceanic plate, which is full of oceanic plateaus, island-arc systems, and seamounts, as the oceanic plate subducts beneath it at an angle (from the southeast). The Australian continental plate to the south has consumed a large sea, collided with the New Guinea arc, and accreted it as the northern part of the island of New Guinea. Oceanic plate motion has sliced off a piece of the Australian plate that now forms the western end of New Guinea and sea floor to the west. It has jammed into the Indonesian island of Sulawesi, east of Borneo. Borneo and the Philippines are themselves composed of many accreted terranes. [Complete global map available from: Marie Tharp, 1 Washington Avenue, South Nyack, New York 10960]*

*Circum-Pacific Terrane Conference held 28 August to 2 September 1983, organized by David Howell and David Jones of the U.S. Geological Survey in Menlo Park, and Allan Cox and Amos Nur of Stanford University. Extended abstracts from the meeting will be available in November from Stanford University Publications.

† *U.S. Geol. Surv. Open-File Rep. 83–716* (1983).

average of 500 kilometers of the western coast of North America are now called.

At first, geologists suggested that Salinia had simply slid north 500 kilometers along the San Andreas from where the Pacific plate had sliced it from a similar continental arc. But Duane Champion and Sherman Gromme of the USGS in Menlo Park with Howell argued that Salinia began its travels much farther south. The shallow inclination of the earth's magnetic field recorded in 70-million-year-old Salinian rocks requires that the rocks formed 2500 kilometers to the south, they say, somewhere in the vicinity of present-day Central America. Such a far-traveled block would qualify as an exotic terrane, only a handful of which have been identified paleomagnetically. Most of those are oceanic—volcanic island arcs that once marked subduction beneath ocean crust—rather than continental like Salinia.

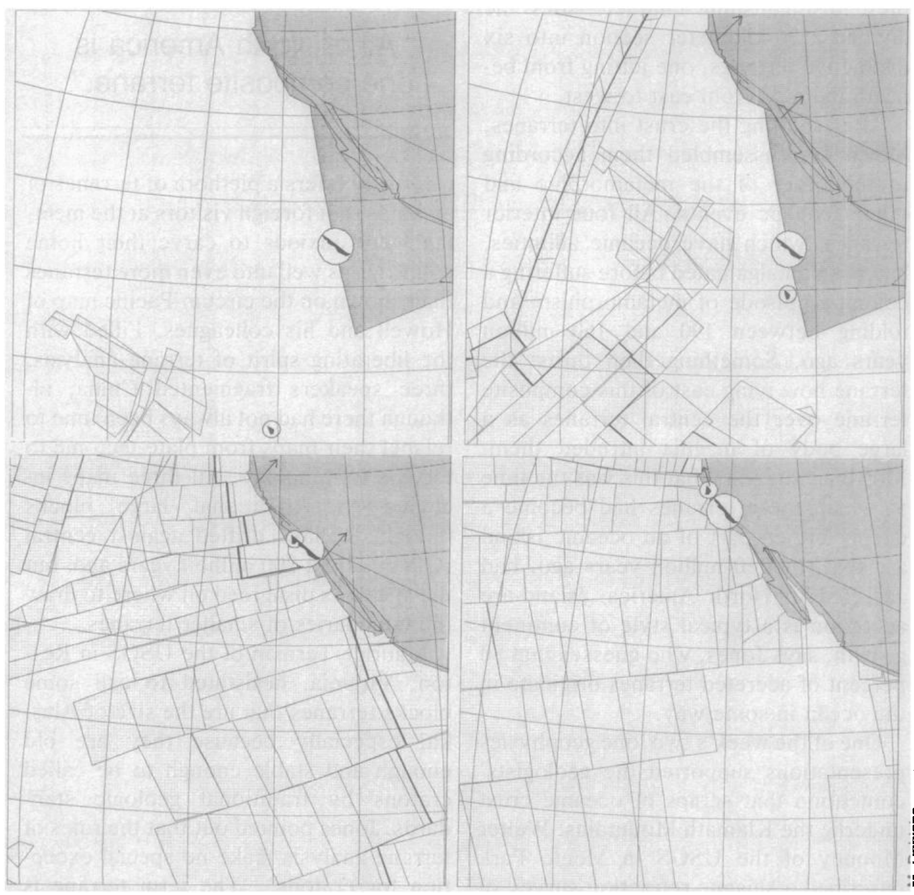
The USGS group also suggested that Salinia did not make the trip alone. By 70 million years ago three companions had fused to it and had begun traveling north as a single composite terrane, according to the group's preliminary paleomagnetic data and geological interpretations. One sign of that amalgamation of terranes is a fan of sediment of that age that now lies intact across the suture between Salinia and the neighboring oceanic crust and sediment of the Stanley Mountain terrane to the west. Another outboard companion was the mélange of the San Simeon terrane; inboard, a pile of slivers of ancient continental crust called the Tujunga terrane fused to Salinia. After amalgamation the entire composite terrane headed north at the brisk pace of 8.5 centimeters per year, according to the paleomagnetic data. By 55 million years ago it had fused to North America in the vicinity of southern California. Once accreted to the North American plate, vertical, strike-slip faults between that plate and the Pacific plate, like today's San Andreas, began dismembering the composite terrane. The strain imposed on it at the plate boundary sliced it up, pulled pieces northward, and rotated them about.

Terrane aficionados emphasized what a mess this makes of the geology of western North America. Subducting oceanic crust still is the only way to make mélange rocks, they note, but a geologist standing on a mélange can no longer assume that subduction took place there. Looking to neighboring rocks may not help. Even if the arrangement of adjacent rocks fits the simple plate-tectonic picture of subduction, the rocks may have formed in two different subduction zones at different times at different places.

All this shuffling about within continental border regions has engendered a "show me" attitude among some geologists. When confronted with adjacent crustal rocks having an uncertain relationship, some terrane specialists, such as Jones, Howell, or Peter Coney of the University of Arizona, are splitting them into two terranes until someone can prove that they are related.

The splitters' approach can make a lot of terranes. Younger rock or sediment can bury the boundary fault or suture between two terranes, or deformation of the boundary can make it unrecognizable. Following a more traditional approach, other geologists might presume that the younger rock hid transitional rocks linking the splitters' two terranes, say sediments from intermediate water depths linking deep-sea sediments and shallow water sediments exposed on either side. Presuming a linkage rather than a gap, these geologists would lump the supposed terranes into a single block. The ultimate lump, said Howell, was the geosyncline, a thick wedge of sediments collected off the coast and shoved inland en masse to extend the continent. The splitters have now carved up the ancient geosyncline of western North America into some of their 200 terranes of western North America, most of which are too small to be shown on the circum-Pacific terrane map.

According to the meeting's organizers, the intent of terrane splitting is the liberation of geologists from the tyranny of the interpretation that is implicit in geologic description. The need to make sense of daunting geologic complexity does not justify undue simplification, they say. Geologists must clearly separate description from subsequent interpretation. They must see terranes first, then consider what they mean. Indeed,



Two far-traveled California terranes

These computer-generated maps, produced by Michel Debiche of Stanford University, show how two terranes, the Salinia (larger circle) and Point Arena (smaller circle), traveled north more than 2500 kilometers to central California. In the upper left figure (105 million years ago), Point Arena starts far to the south, according to paleomagnetic data gathered by Lisa Kanter of Stanford University and by Duane Champion of the USGS. Ocean crust (white and stippled areas) generated at mid-ocean ridges (heaviest lines) carries the Point Arena terrane northward, where it docks with a presumed North American coast (upper right, 80 million years). The same Farallon oceanic plate carries the two along the coast as Point Arena takes the lead (lower left, 35 million years). The Pacific plate now carries them along the San Andreas fault (lower right). The direction of plate subduction (arrows) requires the angled presumed coast for terrane transport.

geologic interpretation received a cool welcome at the meeting. On more than one occasion, Howell rose to object to the use of a simple plate-tectonics diagram illustrating the genesis of particular rocks. Calling them "Dewey-grams" after John Dewey's early 1970's models of subduction and continental collision, Howell complained that they concealed too much complexity and incomplete understanding. Dewey-grams were definitely out for the week.

Interpretation was not verboten, but it often appeared on a smaller scale and always began with the basic unit of the terrane. A study by Nick Mortimer of Stanford of an east-west section of the crust near Yreka in far northern California is an example of how terranes, once split, can be reassembled to explain one aspect of continental growth. Mortimer looked at rock type and the extent to which heat and pressure had altered or metamorphosed the rocks at his site in the northeast Klamath Mountains. Using these distinguishing characteristics, he divided a 30-kilometer section into six distinctive terranes, one jutting from beneath the next from east to west.

After splitting the crust into terranes, Mortimer reassembled them according to the order of the metamorphic and other geologic events. All four interior terranes, which have oceanic affinities, had been amalgamated before suffering a common episode of metamorphism and folding between 190 and 160 million years ago. Something then thrust the terrane now lying east of this composite terrane over the central terranes as a large body of magma intruded them. Mortimer suggests that this was the time at which these terranes had become a deeply buried part of an oceanic island arc that, by 150 million years ago, had accreted to North America. Island-arc accretion is a typical style of continent growth, says Jones, who guesses that 80 percent of accreted terranes originate in the ocean in some way.

One of the week's two lone geophysics presentations supported the geologists' contention that scraps of oceanic crust underlie the Klamath Mountains. Walter Mooney of the USGS in Menlo Park described a seismic refraction survey of northeastern California directed by John Zucca of Menlo Park. In order to probe the deep crust, the USGS group detonated 1000- to 2000-kilogram charges of high explosives and recorded the resulting seismic waves after they had followed nearly horizontal paths through rock layers as deep as 30 kilometers. The character and arrival times of these refracted waves allowed these researchers to map horizontal rock layers having differing seismic wave velocities. The group's geologist-geophysicist, Gary Fuis, led the group's effort to relate seismic velocity to rock type with the aid of surface geology, laboratory measurements of rock velocity, crustal magnetic properties, and comparisons with seismic refraction studies of geologically better known areas.

According to this geologic interpretation, the seismic refraction survey detected as many as four pieces of oceanic crust stacked beneath the Klamath Mountains, just as geologists expected. Also as anticipated, these terranes are not thick blocks that simply docked alongside the continent. Most terranes are bits and pieces, mere scraps, of crust thrust over the edge of the continent during collisions or jammed together during amalgamation at sea.

The western edge of North America, the birthplace of the terrane concept, obviously offers a plethora of terranes of all kinds, but foreign visitors at the meeting were anxious to carve their home countries as well into even more terranes than shown on the circum-Pacific map of Howell and his colleagues. Filled with the liberating spirit of terrane analysis, three speakers fragmented China, although there had not always been time to relabel their maps from plate-tectonic to terrane terminology. All three maps included the traditional large blocks thought to have drifted against central Asia by about 200 million years ago, but the speakers disagreed on where to draw the boundaries of smaller terranes.

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Maurice Terman of the USGS in Reston, Virginia, hesistated to call some blocks terranes that are the size of Alaska, especially because they are old enough and stable enough to be called cratons by traditional geologic standards. Jones pointed out that the rules of terrane analysis make no special exception for cratons. "The term terrane is simply descriptive," he said, "there are no genetic implications. A big terrane is no better than a small one. All of North America is one composite terrane."

Indeed, Howell and his colleagues carry the terrane concept back in time to the origin of continents, attributing the formation of ancient continental cores and their layer-by-layer outward growth to terrane accretion. In an admittedly provocative statement to an earlier meeting, Howell claimed that "Terranes are the only process involved at a fundamental level in determining the growth and shape of continents."

One geologist challenged the meeting's terrane hegemony. Gary Ernst of the University of California at Los Angeles did agree that, in light of terrane accretion and subsequent displacement, continental margins must be far more complicated than geologists had thought. Neither did he object to carving out and naming terranes, as long as they did not shrink to impractical, unmapable sizes. But he cautioned that accretion of exotic terranes could not be the only important way that new rock is added to continents. Ten thousand kilometers of oceanic crust sank beneath the North American continent during the past 180 million years, he noted. All that subduction had to produce large amounts of magma and recrystallization under the conditions that produce rocks of continental composition.

Once in place, said Ernst, this new continental rock could be eroded, carried to the edge of the continent, mixed with bits of seamounts, ocean crust, and deep-sea sediments, and formed into terranes. Subsequent faulting could shuffle them around a bit, but, in Ernst's own analogy, terrane accretion is more like moving cars around in a parking lot than building more cars. "Much of the California margin," he concluded, "may have been formed in place," or at least not far from its present position; Dewey-grams still serve as useful models of continental growth. Although the other informal presentations of the meeting received silent receptions, Ernst's received scattered but sustained applause.

The organizers of the Stanford meeting did not intend that these and other differences that divide the geological community on the subject of terranes would be resolved at the meeting. In fact, dialogue within the geological community has not yet properly defined the nature of the problem. It may well be more a question of terminology than a fundamental schism. In the Franciscan mélange near San Francisco, for example, a terrane specialist can point to pieces of seamounts embedded in the shale as evidence of an exotic, marine origin while another geologist sees huge amounts of shale eroded from continental arcs to the east marked by minor flecks of exotic marine debris. It would seem that geologists must develop more histories of individual terranes in order to determine their role in shaping and enlarging continents.—RICHARD A. KERR