FUTURE SHOCKS
Modern Science, Ancient Catastrophes and the Endless Quest to Predict Earthquakes

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Photographs by Brian Smale

Brian Atwater paddled a battered aluminum canoe up the Copalis River pushed along by a rising Pacific tide. At this point, a 130-mile drive from Seattle, the 100-foot-wide river wound through wide salt marshes fringed with conifers growing on high ground. The scene, softened by gray winter light and drizzle, was so quiet one could hear the whisper of surf a mile away. But then Atwater rounded a bend, and a vision of sudden, violent destruction appeared before him: stranded in the middle of a marsh were dozens of towering western red cedars, weathered like old bones, their gnarly, hollow trunks wide enough to crawl into. "The ghost forest," Atwater said, pulling his paddle from the water. "Earthquake victims."

Atwater beached the canoe and got out to walk among the spectral giants, relics of the last great Pacific Northwest earthquake. The quake generated a vast tsunami that inundated parts of the West Coast and surged across the Pacific, flooding villages some 4,500 miles away in Japan. It was as powerful as the one that killed more than 220,000 people in the Indian Ocean in December 2004. The cedars died after saltwater rushed in, poisoning their roots but leaving their trunks standing. This quake is not noted in any written North American record, but it is clearly written in the earth. The ghost forest stands as perhaps the most conspicuous and haunting warning that it has happened here before—and it will surely happen here again.

"When I started out, a lot of these dangers were not all that clear," says Atwater, a geologist for the U.S. Geological Survey (USGS) who specializes in the science of paleoseismology, or the study of earthquakes past. "If you look at what we know now, it beats you over the head."

Past is prologue for geology's new breed (Brian Atwater in a Washington State 'ghost forest', created by a 1700 earthquake) who are finding ominous signs that devastating earthquakes are more common than once believed.

This article first appeared in the March 2005 issue of SMITHSONIAN and is reprinted here with kind permission of the author.

In one of the more remarkable feats of modern geoscience, researchers have pinpointed the date, hour and size of the cataclysm that killed these cedars. In Japan, officials had recorded an "orphan" tsunami—unconnected with any felt earthquake— with waves up to ten feet high along 600 miles of the Honshu coast at midnight, January 27, 1700. Several years ago, Japanese researchers, by estimating the tsunami's speed, path and other properties, concluded that it was triggered by a magnitude 9 earthquake that warped the seafloor off the Washington coast at 9 p.m. Pacific Standard Time on January 26, 1700. To confirm it, U.S. researchers found a few old trees of known age that had survived the earthquake and compared their tree rings with the rings of the ghost forest cedars. The trees had indeed died just before the growing season of 1700.

In the Pacific Northwest, where written records start in the late 1700s, paleoseismologists have spotted many other signs of past disasters, from sands washed far inshore to undersea landslides. In addition to the risk from offshore earthquakes, recent studies show that Seattle and the greater Puget Sound area, with its four million people, is itself underlain by a network of faults in the earth's surface. They also have ruptured catastrophically in the not-very-distant past. Considering all the geologic evidence, scientists now say a major earthquake strikes the Pacific Northwest every few hundred years—give or take a few hundred years. That means the next one could strike tomorrow.

The study of the past has taken on paramount importance because scientists still cannot predict earthquakes, though not for lack of effort. One important quake-forecasting experiment has taken place since 1985 in tiny Parkfield, California, the self-proclaimed "earthquake capital of the world." The town sits atop a highly active section of the San Andreas fault, the dangerous crack that cuts the state south to north for 800 miles. Due to underlying geological forces, quakes occur in the same places repeatedly. Until recently, much of modern earthquake theory was based on the idea that intervals between these events were nicely regular. Through most of the 20th century, Parkfield, for example, had one every 22 years or so. But experience now shows that quakes are maddeningly unpredictable. Scientists forecast that a quake would hit Parkfield in 1988, give or take five years. They installed networks of strainmeters, creepmeters, seismometers and other instruments around the town. Their goal was to capture precursors to the expected quake, such as a pattern of subtle tremors, that they could later use to predict when

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another quake is imminent. The earthquake did come along—in September 2004, with one-twentieth the expected power—and with no warning whatsoever. Looking at all their measurements, scientists still have found no reliable signs that an earthquake is about to strike.

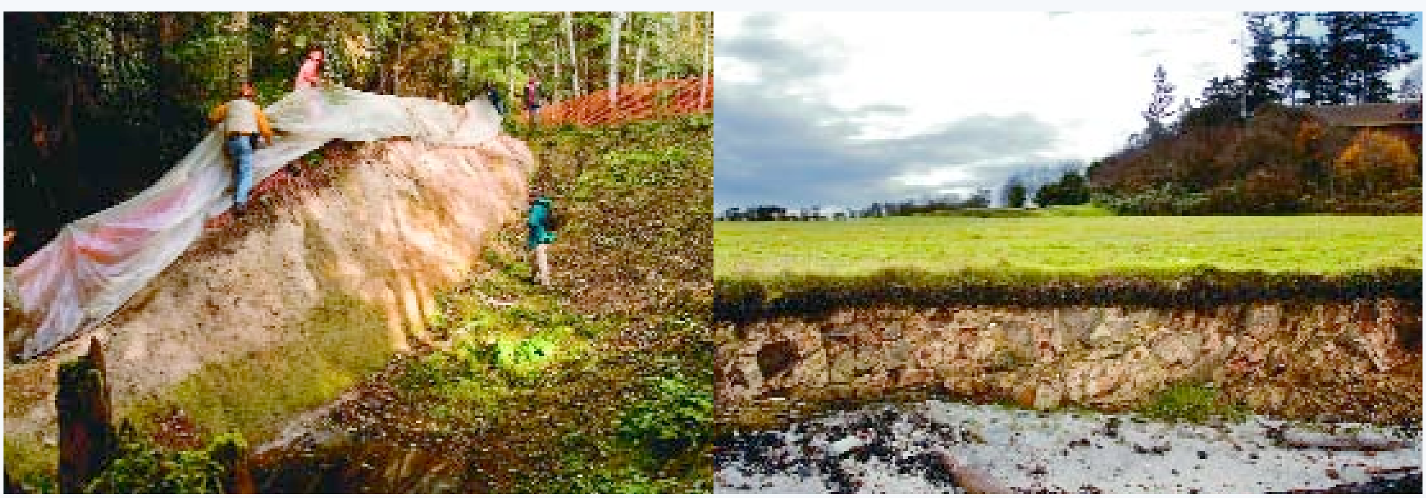
Still, by gathering ever more information about the past, paleoseismologists are becoming adept at mapping danger zones and spreading the warning, even if they can't say when the next one is due. The information, though imprecise, is useful to engineers, city planners and others who can strengthen building codes and educate the public about how to survive a major quake whenever it comes. Art Frankel, a chief architect of the USGS national seismic hazard mapping project, says such geological "hazard maps" are like charts of the most dangerous traffic intersections; they can't predict when the next car accident will happen, but they do tell you to watch out.

Due to these studies of past earthquakes, the world is looking ever more inhospitable. Paleoseismology is turning up portentous signs of past upheavals in the U.S. Midwest, eastern Canada, Australia and Germany. "We're discovering some new hazard every few months," says Brian Sherrod, a USGS geologist investigating the Seattle faults. The Pacific Northwest may not be the only place harboring such nasty surprises, but it is where the geological signs are most dramatic, the science is moving fast, and a future earthquake would be among the most catastrophic.

The earth's crust consists of interlocking tectonic plates that float on the hot, pliable interior of the planet, drifting and colliding with one another. The Pacific Northwest coast is such a dangerous place because it rests on a continental plate that meets, some 30 to 90 miles offshore, a seafloor plate. The boundary between the two plates, stretching 700 miles from British Columbia to Northern California, is called the Cascadia subduction zone. Subduction is the process by which an ocean plate nudges under a continental plate, usually by a few inches a year. Grinding between such plates can bring small temblors, but often the parts lock against each other like sticky watch gears, causing the still advancing seafloor to compress like a spring and the overlying coastline to warp upward. When the pent-up pressure finally pops, the seafloor lunges landward and the coast lunges seaward, with seaside real estate collapsing. The shifting plates displace seawater in all directions, creating a tsunami that travels up to 500 miles an hour. These subduction-zone quakes are the world's largest, dwarfing those that take place in the land's crust. December's subduction quake in Indonesia, a magnitude 9, was about 30 times more powerful than the 1906 San Francisco event that took place in the continental crust near the city. Other major subduction-zone quakes off Alaska in 1946 and 1964 sent tsunamis all the way to Hawaii and Northern California, killing scores of people.

Downriver of the ghost forest, with heavy rain threatening the tidal estuary of the Copalis River, Atwater stepped from the canoe to stand crotch-deep in cold water and mud. He wore hiking boots and chest waders, having learned long ago that tidal mud can suck hip waders right off of you. Wielding an entrenching tool, a military folding shovel, he chopped at the riverbank to view the sedimentary layers, which can yield a great deal of information about past quakes. Every time a seafloor earthquake occurs here, forests and marshes suddenly drop, and are reburied by later sediments washed in by tides and river drainage. A geologist can dig a hole in search of such buried evidence—or find a riverbank where erosion has done most of the work for him, which was what Atwater had here. His tool kit also included a hunting knife and a nejiri gama, a trowel-size Japanese gardening tool shaped like a hoe.

Atwater kneeled in the shallows and scraped riverbank mud down onto his thighs, then smoothed the bank with the nejiri gama. Below the two and half feet of brownish tidal muck lay a half-inch band of gray sand, which was neatly draped over black peat. The peat was laced with tree roots, even though the nearest visible tree was far across the marsh. "Hoo, that's nice, that's fresh!" Atwater shouted. "Old dependable!" These trees grow only above the tide line and were now below it. Something, he said, had dropped this ecosystem several feet all at once; all signs point to a seafloor quake. Radiocarbon dating has shown the plants died about 300 years ago. The overlying sand sheet was the clincher: only a tsunami could have laid it down.



Signs of past seismic activity may be hidden (geologists inspect contorted sediment layers within a fault excavated outside Seattle) or in plain sight (a marine shelf on Puget Sound was lifted about 20 feet by a quake in the year 900).

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Atwater, 53, has been combing the region since 1986 for evidence of past earthquakes, and his work at a dozen estuaries— in addition to other scientists' findings—has revealed not only the great 1700 earthquake and tsunami but also a dozen other major quakes over the past 7,000 years. Recent seafloor studies off the Pacific Northwest coast tell the same story. Overall, big subduction-zone quakes strike on average every 500 to 600 years. But the intervals between them range from 200 to 1,000 years. "If we can predict that we're in a short interval, we've essentially used up our time. But we can't predict," says Chris Goldfinger, a marine geologist at Oregon State University. Recent studies using satellite-controlled global-positioning systems and other new technology confirm that the region's tectonic plates are converging and locked together. In some places, the Washington and Oregon coastlines are rising by 1.5 inches a year. As Atwater points out, "That doesn't sound like much until you multiply it by, say, 1,000 years, and you get ten feet." And if the land has risen that far, it could drop that far when a quake comes, just like the layer of peat Atwater uncovered in the tidal estuary. "The bulge will collapse during the next earthquake, and there will be new ghost forests," he says.

We paddled farther up the Copalis to the mouth of a small creek, where Atwater located the 1700 tsunami sand sheet's continuation in the riverbank. With his nejiri gama, he dug out clumps of perfectly preserved ancient spruce needles, apparently cast up by the great waves. Nearby he uncovered a shard of fire-cracked rock—evidence of a cook fire. "That's spooky," he says. "It makes you wonder what happened to these people." Paleoseismology has shed new light on legends by aboriginal coastal peoples such as the Yurok and the Quileute. Many stories describe times when the earth shook and the ocean crashed in, wiping out villages, stranding canoes in trees and killing everyone but the fastest or luckiest. Storytellers often explained these events as the result of a battle between a great whale and a thunderbird. "Well before settlers came here, Native peoples dealt with earthquakes," says James Rasmussen, a councilman for the Duwamish people in Seattle. Archaeologists have now identified many sites that contain pottery and other artifacts that were submerged by rising waters. Apparently, Native people over the years moved closer to the shore or fled it as thunderbird and whale fought it out.

Like rain, a certain amount of worry about earthquakes and tsunamis (a sign on the coast) is given in the Pacific North west.

Today, of course, we're not so light on our feet. A recent study estimates that ten million people on the U.S. West Coast would be affected by a Cascadia subduction-zone quake. Three hundred years of tectonic pressure has now built up. The shaking from such a quake, lasting two to four minutes, would damage 200 highway bridges, put Pacific ports out of business for months, and generate low-frequency shock waves possibly capable of toppling tall buildings and long bridges in Seattle and Portland, Oregon. A tsunami of 30 feet or more would reach parts of the Pacific Coast in little over half an hour. Of special concern to Washington State officials are places like the coastal resort town of Ocean Shores, on a long sand spit with a narrow access road that serves 50,000 visitors on a summer day. Here, the highest ground—26 feet above sea level—would hold only "about 100 people who are very good friends," says Tim Walsh, state geological hazards program manager. He suggests that the town consider "vertical evacuation"—building multistory schools or other public structures in which people on the top floors could escape a tsunami, assuming the buildings themselves could withstand the impact. To flee a tsunami, people need warnings, and the U.S. government has set out Pacific Ocean monitors to pick up signals from known danger spots, not only in the Pacific Northwest, but in Japan, Russia, Chile and Alaska as well. This system is designed to transmit warnings to countries across the basin within minutes. Similar networks are planned for the Atlantic and Indian oceans.

In Washington State, officials are trying to educate a public that has regarded the threat casually—but may now pay a lot more attention with the Indian Ocean tsunami as an object lesson. A warning sign can be seen by the roadside. A few weeks before the disaster, Atwater and Walsh drove to Port Townsend, a Victorian-era seaport on the Strait of Juan de Fuca, about midway between Seattle and the open ocean, where they ran a tsunami workshop that was attended by only a handful of emergency officials and a few dozen residents. Walsh pointed out that a tsunami might take a couple of hours to reach Port Townsend, which has nearby cliffs for retreat. The town is dotted with blue-and white tsunami warning signs. Unfortunately, they are a popular souvenir. "Just please stop stealing the signs," Walsh chided the audience as he handed out free paper replicas of the signs.

"A lot of people think of tsunamis as some kind of cool adventure," Walsh said after the meeting. He remembered that following a big 1994 seafloor quake off Russia's Kuril Islands, surfers in Hawaii headed for the beaches. A film crew actually set up at the surf line on the Washington coast, hoping to catch a giant wave that, fortunately for them, never came. Walsh said, "I think they won't be doing that next time."

Brian Sherrod, a geologist with the USGS in Seattle, has rush-hour traffic to thank for one discovery. Recently he led some visitors under Interstate 5, a ten-lane raised artery traversing the city's downtown, as thousands of northbound cars and trucks thundered overhead. He pointed to the ground beneath one of the massive concrete supports, where the ruptures of an earthquake fault in prehistoric times had tortured the usually flat sediment layers into broken waves, then smashed and bent them backward so that lower ones were shoved over the upper—as if someone had taken a layer cake and slammed a door on it. This is one of many scary signs from Seattle's past, though one of the few visible to the naked eye. "I spotted this when I was stopped in

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Friday-afternoon traffic," said Sherrod, pointing to the southbound lanes, 50 feet away at eye level. "I was singing real loud to the radio. Then I stopped singing and yelled, 'Holy sh-t!' "

Earthquakes have long been a fact of life in Seattle. Each year, inland Washington gets a dozen or so quakes big enough to feel, and since 1872 about two dozen have caused damage. Most cluster under the Puget Sound lowland, the heavily developed run of bays, straits, islands and peninsulas running through Seattle south to Olympia. Larger-than-usual quakes in 1949 and 1965 killed 14 people. In the past few decades, building codes have been upgraded and a network of seismometers installed across Washington and Oregon. Those instruments showed that most of the smaller quakes are shallow readjustments of the earth's crust—rarely a big deal. The more sizable events, like quakes in 1949 and 1965, typically emanate from depths of 30 miles or more. Fortunately, this is far enough down that a lot of energy bleeds from the seismic shock waves before they reach the surface. The most recent big deep one was the February 28, 2001, Nisqually quake— magnitude 6.8, as measured at its 32-mile-deep point of origin. It damaged older masonry buildings in Seattle's picturesque Pioneer Square shopping district, where unreinforced bricks flattened cars; at the vast nearby cargo harbor, pavement split and sand volcanoes boiled up. Though damage was some $2 billion to $4 billion statewide, many businesses were able to reopen within hours.

One of the first hints that monstrous quakes take place near Seattle's surface, where they can do catastrophic damage, came when companies were hunting for oil under Puget Sound in the 1960s, and geophysicists spotted apparent faults in the Sound's floor. Into the 1990s, these were presumed to be inactive relic faults; then scientists looked more closely. At Restoration Point, on populous Bainbridge Island across Puget Sound from downtown Seattle, one USGS scientist recognized evidence of what geologists call a marine terrace. This is a stair-step structure made of a wave-cut sea cliff topped by a flat, dry area that runs up to several hundred feet inland to a similar, but higher cliff. Restoration Point's sharp, uneroded edges, and ancient marine fossils found on the flat step, suggested the whole block had risen more than 20 feet from the water all at once. Several miles north of the point lies a former tideland that apparently had dropped at the same time. These paired formations are the signature of what's known as a reverse fault, in which the earth's crust gets shoved up violently on one side and down on the other. This one is now called the Seattle fault zone. It runs west to east for at least 40 miles, under Puget Sound, downtown Seattle (cutting it in half) and its suburbs, and nearby lakes.

Along the Seattle fault on the east side of the city, Gordon Jacoby, a Columbia University tree-ring specialist, has identified another ghost forest—under 60 feet of water in Lake Washington. The trees did not sink; they rode off a nearby hill on a gigantic quake-induced landslide in the year 900, apparently at the same time that Restoration Point rose. Yet more evidence of that devastating event surfaced a decade ago several miles north of the Seattle fault. The city was digging a sewer, and Atwater spotted in one of the excavations an inland tsunami deposit—the first of many tied to that quake. The tsunami came when the fault thrust up under Puget Sound, sending out waves that smashed what is now the booming metropolitan waterfront.

Geologists have spotted at least five other fault zones in the region, from the Canadian border south to Olympia. The faults bear signs of half a dozen ruptures over the past 2,500 years, and one fault, the Utsalady, just north of Seattle, might have ruptured as recently as the early 1800s. The evidence amassed so far suggests an average repeat time for a major shallow continental earthquake from centuries to millennia.

The USGS has mounted a campaign to map the faults in detail. To do this, scientists use what they call active-source seismics—creating booms, then tracing vibrations through the earth with instruments to detect where subterranean breaks interrupt rock layers. Friendly Seattleites almost always let them dig up their lawn to bury a seismometer, and let them hook it to their electricity. Some neighbors even compete to land one of the instruments, out of what USGS geophysicist Tom Pratt calls "seismometer envy."

To create the vibrations, scientists have used air guns, shotguns, sledgehammers, explosives and "thumpers"—piledriver- type trucks that pound the ground with enough force to rattle dishes. (A few years ago scientists had to apologize in the morning paper after one nighttime blast alarmed residents who thought it was an earthquake.) The USGS also made the most of the city's demolition of its aging Kingdome stadium with explosives in 2000. "We said to ourselves: 'Hey, that's gonna make a big boom!' " says Pratt, who helped plant 200 seismometers to monitor the event.

One day, Atwater and USGS geologist Ray Wells took a ferry to Restoration Point. The flat lower terrace is now a golf course, and on the cliff above people have built expensive homes. From here, the scientists pointed out the invisible path of the fault under Puget Sound toward Seattle, past a ten-mile strip of shipping-container piers, petroleum tank farms and industrial plants, to the city's passenger ferry docks—the country's busiest. As the fault reaches land, it crosses under the waterfront Alaskan Way

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Viaduct, a 1950s vintage raised double-decked highway that almost collapsed in the 2001 Nisqually quake and is guaranteed to pancake with anything bigger. (Many geologists avoid driving on it.) Next, the fault passes crowds of skyscrapers up to 76 stories high, and under the two new stadiums housing the Seattle Seahawks football team and Mariners baseball team. It cuts beneath I-5, proceeds under a steep knoll topped by the headquarters of Amazon.com and forms the southern shoulder of I-90, and heads out to the rapidly growing suburbs around Lake Sammamish.

That is just the Seattle fault; the others zigging across the region could well be connected to it. Many scientists say it is even possible that the faults' activities are connected by some grand mechanism to the great subduction-zone quakes out at sea, for many of the inland quakes seem to have occurred around the same times as those on the seafloor. But the inland mechanics are complicated. According to one currently popular theory, Washington is being pushed by Oregon northward, up against Canada. But Canada is not getting out of the way, so Washington is folding like an accordion, and sometimes those folds—the east-west faults—break violently. "Most people don't want to come right out and say it, but it is all probably linked together in some way we don't understand," says the USGS's Art Frankel.

"My colleagues and I describe this region as a geological train wreck," says USGS geologist Ray Wells (on Bainbridge Island where researchers have cut away a Seattle fault offshoot).

Geologists have found active faults (one runs by Puget Sound's Restoration Point, to Seattle).

Geophysicists recently created a stir when they discovered that the deeper part of the ocean slab, subducting from the west under southern British Columbia and northern Washington, slips with uncanny regularity—about every 14 months—without making conventional seismic waves. No one knows if this "silent" slip relieves tension in the offshore subduction zone or increases it—or if it could somehow help trigger inland quakes. This spring, geophysicists funded by the National Science Foundation will drop instruments into eight deep holes bored into the Olympic Peninsula, west of Seattle, in hopes of monitoring these subtle rumblings. In addition, 150 satellite-controlled global-positioning instruments will be set out across the Northwest to measure minute movements in the crust.

In any event, Seattle is one of the world's worst places for an earthquake. A scenario released last month by a joint private-government group estimates the damage from a 6.7 magnitude shallow crustal quake at $33 billion, with 39,000 buildings largely or totally destroyed, 130 fires burning simultaneously and 7,700 people dead or badly hurt. Part of the city sits on a soft basin of poorly consolidated sedimentary rocks, and like a bowl of gelatin this unstable base can jiggle if shocked, amplifying seismic waves up to 16 times. The harbor sits on watery former tidal mud flats, which can liquefy when shaken. One computer model shows a ten-foot tsunami roaring from Puget Sound over the Seattle waterfront to mow down cargo and passenger docks, and advancing toward the U.S. Navy shipyards in Bremerton. Even one major bridge collapse would paralyze the city, and engineers predict dozens. Seattle has a lot of high ground—some hillsides are so precipitous that driving up city streets can make ears pop—so landslides, already common in heavy rains, are predicted by the thousands.

The city is getting ready, says Ines Pearce, a Seattle emergency manager. A stricter building code was adopted last year. Raised-highway supports are being retrofitted to keep them from crumbling. Firehouse door frames are being reinforced to keep trucks from being trapped inside. Some 10,000 residents have been organized into local disaster response teams. Schools have removed overhead flush tanks and other hazards, and students duck under their desks in monthly "drop, cover and hold" earthquake exercises reminiscent of 1950s atomic bomb drills. But the preparations may not be enough. Tom Heaton, a California Institute of Technology geophysicist who first theorized the subduction threat to the Pacific Northwest and is now analyzing Seattle's infrastructure, says that even resistant structures may not survive a major crustal quake or one from the subduction zone. "Earthquake engineers base their designs on past mistakes. No one's ever seen ground shaking like what would occur in a giant earthquake," he says.

Down in the basement of his home, on a leafy Seattle street, Brian Atwater pointed out where he spent $2,000 in the 1990s to reinforce his wooden house frame and bolt it to the concrete foundation, to better secure it. During the Nisqually quake, cracks broke out all over his plaster walls, and his chimney got twisted and had to be replaced. But the house didn't go anywhere. If something worse comes along, he hopes the reinforcing will allow his family to escape alive and salvage their possessions.

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But there are some risks Atwater is willing to abide. On the way back from fieldwork one night recently, he was driving toward his house when he swung his pickup truck away from I-5—the obvious route—onto the dreaded Alaskan Way Viaduct. Wasn't he nervous? "I'd rather take my chances here," said Atwater, bumping along high over the lights of docks and ships in the harbor. "People over on I-5, they drive too crazy." R

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