Over the top. The 11 March tsunami overwhelmed a coastal seawall in Miyako City designed for lesser waves.

JAPAN DISASTER

Scientific Consensus on Great Quake Came Too Late

TOKYO—Ten years ago, Koji Minoura, a geologist at Tohoku University in Sendai, and colleagues injected some science into a legendary disaster. A historical document compiled in 901 C.E. told of an earthquake in 869 C.E. that destroyed a castle town in northeastern Japan and a subsequent tsunami that inundated the surrounding area, killing 1000. Digging in rice paddies in what is now called the Sendai Plain, Minoura's team found telltale marine sediments showing that the tsunami ran as much as 4 kilometers inland. They estimated the Jogan earthquake's magnitude at 8.3 and concluded that it could recur at 1000-year intervals. "The possibility of a large tsunami striking the Sendai Plain is high," they wrote in a 2001 article in the *Journal of Natural Disaster Science*.

That obscure paper is now at the center of a growing debate about how quickly scientific findings can and should influence disaster-mitigation policies. A few years before the magnitude-9.0 Tohoku earthquake struck northeastern Japan on 11 March, a scientific consensus had begun to coalesce around the idea that a Jogan-like event could happen again. But that consensus did not influence seismic risk assessments, tsunami preparedness, or a review of the hardiness of the Fukushima Daiichi nuclear power plant.

"It's necessary to communicate research findings to society," says Yukinobu Okamura, a geologist at the Active Fault and Earthquake Research Center in Tsukuba, who led studies that independently bolstered Minoura's findings. "We tried to do that in this case, but we weren't in time."

One lesson is that incorporating geological studies of ancient earthquakes and tsunamis into risk assessments "is essential to compensate for the limitations in the current evaluation scheme," says Fumihiko Imamura, a tsunami engineer at Tohoku University in Sendai.

The need to revise earthquake probability analyses extends far beyond Japan. "There are other subduction zones, near Java and New Zealand, where people think there is no chance of a big quake" because they cling to old models of seismic processes, says Robert McCaffrey, a geophysicist at Portland State University in Oregon. But forecasts are generally based on studies covering the past several centuries—"not long enough for the cycle time for these big earthquakes," he says.

Although scientists have been interrogating geologic deposits for clues to the size and frequency of major earthquakes for several decades, efforts to apply such techniques to ancient tsunamis are more recent. In the early 1990s, "many people didn't believe tsunamis left deposits," says Joanne Bourgeois, a tsunami geologist at the University of Washington, Seattle. Minoura was among the paleotsunami pioneers when he started digging in the Sendai Plain. Recent sediment surveys have supported his Jogan findings, while studies of accumulating crustal strain in the Sendai area hinted at the possibility of a major earthquake. Even so, before the 11 March quake some scientists "did not believe" the region was primed for a big earthquake, says Yuichiro Tanioka, a seismologist at Hokkaido University in Sapporo.

Planners and engineers began to recognize the significance of geologic research for earthquake preparedness in the late 1970s, after paleoseismic studies revealed the regular recurrence of earthquakes along the San Andreas fault in California. But paleo studies didn't directly influence public policy until the mid-1990s. An early example is the Cascadia earthquake, now known to have occurred in the subduction zone off North America's Pacific Coast in 1700. In 1986, researchers reported the first geological evidence for this massive event: a sudden drop in elevation of coastal regions, inferred from sedimentary deposits, a sign of slippage on the upper side of a subduction zone. Eight years later, a revision to the Uniform Building Code required buildings in western Washington and Oregon to be 50% more earthquake-resistant. Then in 1995, partly because of the Pacific threat, the U.S. Congress passed the National Tsunami Hazard Mitigation Program, which supports studies of tsunami risk and emergency planning.

The size and timing of the Cascadia earthquake were unclear. Those pieces of the puzzle turned up in Japan, where Kenji Satake, a seismologist now at University of Tokyo, and colleagues found Japanese accounts of a tsunami without an apparent local cause. In *Nature* in 1996, they pinpointed the date of the Cascadia earthquake as 26 January 1700 and estimated a magnitude of 9.0. "There is a lot of respect for [Japan's] record-keeping diligence," says Brian Atwater, a U.S. Geological Survey geologist at the University of Washington, Seattle.

Japan's Headquarters for Earthquake Research Promotion produces seismic hazard maps for the nation; they are used to estimate potential tsunamis. The headquarters incorporates paleoseismic studies in determining earthquake risk—but only in Hokkaido, Tanioka says. Hokkaido was the last region of modern Japan settled by ethnic Japanese, and

CREDIT: REUTERS

Published by AAAS

reliable records go back only to the mid-1800s, he says. Elsewhere, the agency relies on "documents allowing the estimation of earthquake frequency and scale [going] back 400 years," Imamura says. Using those records, the earthquake research headquarters warned that the area hit by the 11 March temblor faced a 99% probability of a magnitude-7.5 earthquake occurring in the next 30 years.

Okamura and colleagues conducted more extensive surveys in the Sendai area in the mid-2000s that bolstered Minoura's original findings. According to Okamura, the earthquake research headquarters was studying whether and how to include Jogan in its risk assessment for the Tohoku region. "But the earthquake occurred before the evaluation was completed," he says.

Any upward revision is now also too late for the Fukushima plant. The first reactor was completed in 1971, long before the Jogan event appeared on the scientific radar. Planners girded for a maximum 5.7-meter tsunami; Tokyo Electric Power Co. estimates that the tsunami that took out the backup diesel generators was 14 meters high. The company missed a chance to address the deficiency when an expert panel reviewed the plant's seismic resistance in 2008. As *The Washington Post* reported, Okamura told the panel about the Jogan earthquake and warned that a bigger tsunami was possible. The panel, concerned mostly about earthquake shaking, brushed aside his concerns, he asserts.

Japan and other countries will surely rethink tsunami threats—just as Minoura intends to do. Originally, he says, he tried to "simply make clear the geological process of coastal environments." But now, "I want to meditate deeply on the future of geological work [related to] tsunamis," he says. The Tohoku temblor should convince the scientific community and authorities that magnitude-9 earthquakes can occur anywhere along subduction zones, McCaffrey says. Like a tsunami, the effects of the 11 March Tohoku earthquake will spread far and wide.

–DENNIS NORMILE

ARCHAEOLOGY

In Indus Times, the River Didn't Run Through It

SANTA FE—The Saraswati was the mother of all the holy rivers of India, flowing between the Ganges and the Indus and dispensing milk and ghee before it dried up, according to ancient Hindu scripture. Archaeologists and some devout Hindus have long tried to pinpoint its course, which the scripture puts between the Indus and Ganges rivers. For more than a century the best candidate has been the ancient channels of the now-dry Ghaggar-Hakra system in today's India and Pakistan. Along its course are scattered settlements of the Indus civilization, which some Hindus see as the progenitor of their traditions.

At a meeting* here last week, however, three independent teams offered preliminary evidence that the Ghaggar-Hakra was at most a modest seasonal stream during and after the Indus flourished from 2500 B.C.E. to 1900 B.C.E. "We need more cores, but the data suggests there was no big river here" in Indus times, said geologist Sanjeev Gupta of Imperial College London in his talk.

The findings puzzle and intrigue archaeologists. The Indus settlements along the Ghaggar-Hakra appear to have migrated over time toward the river's source. That has been interpreted by some as a sign of decreasing river flow and stress on the Indus society. If, however, the river was dry or only seasonal, it may prompt a re-evaluation of how Indus peoples acquired water for agriculture. "This is enormously important work," says archaeologist Rita Wright of New York University in New York City, who heard the presentations. "We may have to give up the idea of the Indus as a civilization based on rivers."

To determine when the Ghaggar-Hakra last was an active river, researchers looked for the youngest sediments deposited by flowing water. Each of the three groups dated sediments primarily with optically stimulated luminescence, a technique that uses the light energy stored in quartz grains to estimate when the grains were last exposed to light. Gupta's team drilled several 40-meter cores near the Indus city of Kalibangan, in today's India, and found that river sediment deposits ceased after approximately 14,000 B.C.E., long before the Indus culture. Gupta said in his talk that the river may have jumped into the bed of the Sutlej River to the west at this time. Hideaki Maemoku of Hiroshima University led a Japanese team that found that sand dunes surrounding the Ghaggar-Hakra are older than 10,000 years, another indication any river present had long since dried up by that point. Maemoku's poster gave this summation of the would-be Saraswati: "No, it wasn't mighty."

Based on work downstream in Pakistan, another team, led by geologist Peter Clift of the University of Aberdeen in the United Kingdom, agrees that little water flowed regularly in the system after 2500 B.C.E. But Clift believes the river may have simply shifted to another as-yet-unidentified channel and that there still may have been flow in the Ghaggar-Hakra during Indus times.

Dry hole. Researchers drill a core (*top*) in the bed of the ancient Ghaggar-Hakra River in India.

CREDITS (TOP TO BOTTOM): RAJIV SINHA/IIT-KANPUR; M. TWOMBLY/SCIENCE

Clift says the drying of the Ghaggar-Hakra may reflect a drought that may yet help explain the civilization's mysterious decline. However, other researchers note, even though no surface water flows today, the ancient channels still provide groundwater for farmers and might have done so in the past. And a dried-up riverbed may have been a safer place to settle than the banks of a major river such as the Indus, which flooded disastrously in 2010. "Now we have more questions," Wright says.

–ANDREW LAWLER

*American Geophysical Union meeting, "Climates, Past Landscapes and Civilizations," 21–25 March 2011, Santa Fe.

Published by AAAS