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Progress Made in Understanding Mount Rainier's Hazards

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At 4392 m high, glacier-clad Mount Rainier dominates the skyline of the southern Puget Sound region and is the centerpiece of Mount Rainier National Park. About 2.5 million people of the greater Seattle–Tacoma metropolitan area can see Mount Rainier on clear days, and 150,000 live in areas swept by lahars and floods that emanated from the volcano during the last 6,000 years (Figure 1). These lahars include the voluminous Osceola Mudflow that floors the lowlands south of Seattle and east of Tacoma, and which was generated by massive volcano flank-collapse. Mount Rainier's last eruption was a light dusting of ash in 1894; minor pumice last erupted between 1820 and 1854; and the most recent large eruptions we know of were about 1100 and 2300 years ago, according to reports from the U.S. Geological Survey.

The large population at risk and the dearth of information about Mount Rainier's edifice geology, pre-Holocene history, and hydromagmatic system prompted its inclusion as one of 16 volcanoes worldwide targeted for intense, multidisciplinary research as part of the United Nations' International Decade for Natural Disaster Reduction (IDNDR). Hazards that led to Decade Volcano designation stimulated much new research by many workers in understanding hazards from Mount Rainier.

Holocene lahar deposits are the fundamental evidence of Mount Rainier's volcanic hazards and are the basis from which response plans have been developed. Information on these lahars were first collected in the 1950s and reached maturity in the early 1990s. Subsequent research has greatly increased understanding of how and where lahars originate at Mount Rainier, reducing speculation and modifying, but mostly bolstering, confidence in the lahar-based hazard forecasts.

Growth and Eruptive Style

Modern Mount Rainier began to grow at very close to 500 ka, atop the remnants of a 1–2 Ma volcanic center that had been almost completely removed by erosion (Figure 2). Effusions of andesite and low-SiO_2 dacite lavas have dominated Mount Rainier's eruptions. Lava domes are almost unknown on Mount Rainier, unlike nearby Mount St. Helens, but block-and-ash pyroclastic flows erupted throughout Mount Rainier's history. True basalts are absent, but basaltic andesite forms minor flank-fed lava flows and is widespread as quenched inclusions in andesite-dacite lavas, and basaltic andesite appears to be the immediate parent feeding Mount Rainier's magmatic system. Lava flows extend up to 22 km radially from the present summit location, and individual far-traveled flows have volumes up to 9 km^3.

Fortunately, eruptions of such voluminous and far-reaching lavas were restricted to two episodes of high effusion rates from 500 to 420 ka and 280 to 180 ka (Figure 2), and are unlikely today. Lavas erupted outside these high-effusion periods are more representative of likely activity and have generally traveled no farther than 10 km from the summit, and most have volumes less than 0.5 km^3. When Mount Rainier next erupts lava, the flows will most probably be restricted within or extend only slightly beyond the extent of present-day glaciers. Although a survey of historic lava flows [*Major and Newhall*, 1989] at glaciated volcanoes suggests that lavas entrenched in snow and ice cause only small floods and lahars, lava flows flowing on the precipitous ice-clad slopes of Mount Rainier may break up, avalanche, and form much larger lahars.

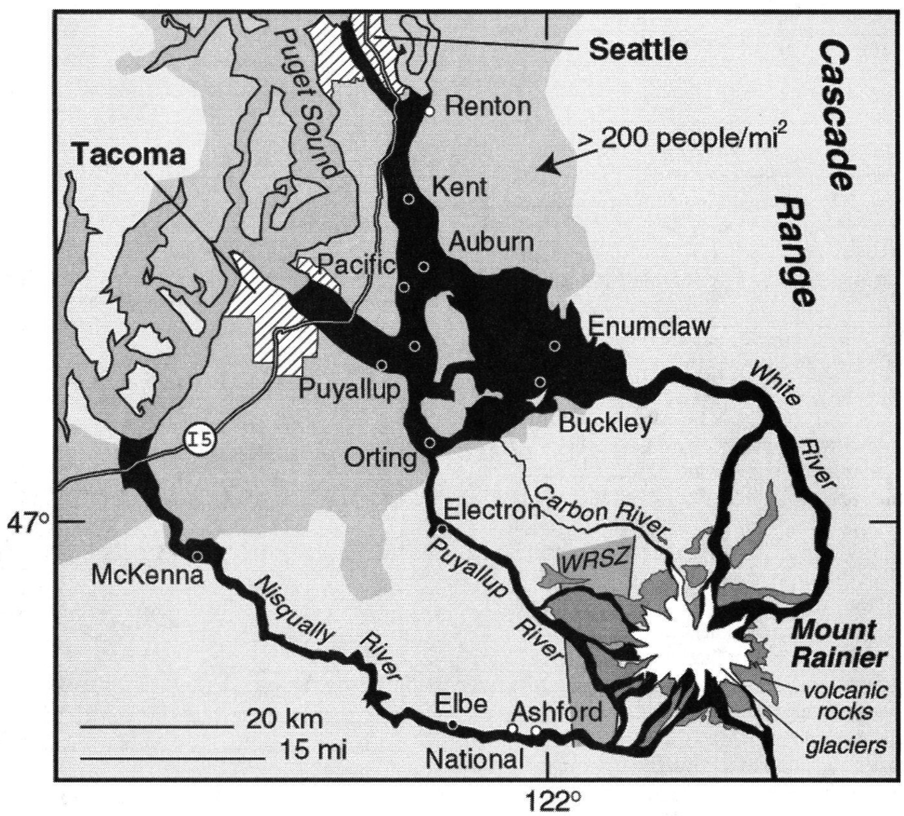

Fig. 1. Map showing area (black) inundated by lahars or associated floods from Mount Rainier in the last 6000 years [modified from Scott and Vallance, 1995; extension to City of Seattle by P.T. Pringle, unpublished mapping, 2000]. Symbols: towns (dots); city limits of Seattle and Tacoma (lined fields); Mount Rainier volcanic rocks (red); interstate highway 5 (double lines); west Rainier seismic zone (WRSZ, blue). Original color image appears at the back of this volume.

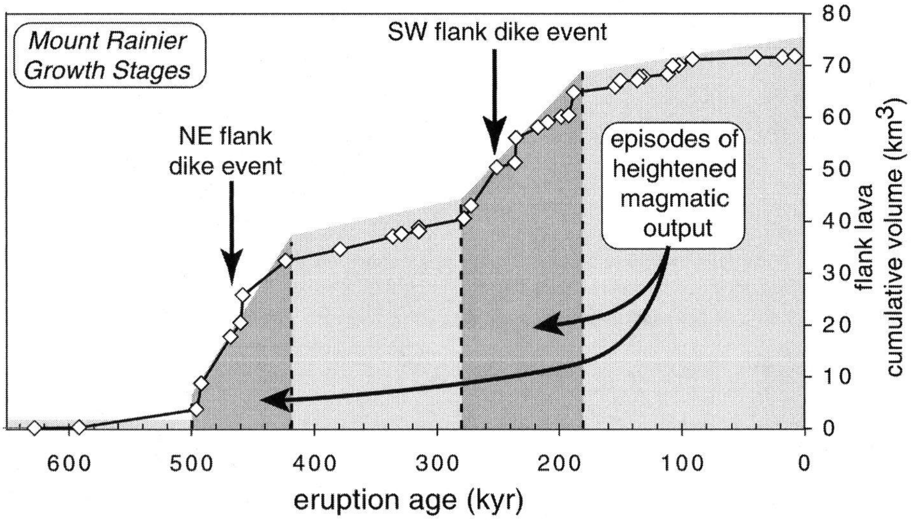

Fig. 2. Cumulative growth curve for flank lavas from Mount Rainier, based on new geologic mapping and K-Ar and Ar-Ar dating by T. W. Sisson and M. A. Lanphere [1999]. Each symbol represents a mapped and dated flank flow or flow group. Emplacement of large dikes indicated by arrows. The total edifice growth curve is not shown because of imprecise volume estimates.

Block-and-ash pyroclastic flows accompanied dominant lava eruptions throughout the volcano's history and probably pose a greater hazard than lava flows, but pre-Holocene pyroclastic flow deposits had gone largely unrecognized prior to new mapping in the 1990s. Pyroclastic flows are hazardous at Mount Rainier mainly because they can sweep across, incorporate, and melt glacial snow and ice and thereby form lahars that can travel far from the volcano. Pyroclastic flows that move across glaciers commonly do not weld and do not leave long-lasting deposits; hence, their proportion in the rock record of Mount Rainier, 10–20% by volume, under-represents the proportion in which they erupted. Dome collapse has been the most widely observed cause of block-and-ash flow eruptions at other volcanoes. Only one lava dome is exposed at Mount Rainier, so pyroclastic flows derive from other processes such as vent clearing explosions, voluminous hydromagmatic eruptions, or the sudden failure of thick, viscous lavas flowing over steep headwalls.

Consequently, pyroclastic flows at Mount Rainier are most likely to be preceded by lava flow extrusion or nothing more than a brief period of unrest. The volcano supports large glaciers on all its sides; hence, pyroclastic flows and the lahars they cause threaten all the valleys that head on the volcano.

In contrast to Mount St. Helens, Mount Rainier has erupted modest amounts of pumice in Holocene time. Voluminous pumice-fall deposits are rare but not unknown in Mount Rainier's Pleistocene record. The two largest preserved pumice-fall deposits were erupted near the ends of the two periods of high effusion rates. One of these pumice deposits forms a conspicuous 20-m-thick white band in Sunset Amphitheater headwall, high on the west flank of the volcano, which is readily seen from the southern Puget Sound lowlands.

Comparisons with deposits from other volcanoes suggest that these Pleistocene pumice falls were in the range of 1–6 km^3 (0.3–1.7 km^3 as dense rock), similar to all but the largest Holocene pumice eruptions of Mount St. Helens. As with the large-volume, far-traveled lava flows, such voluminous pumice eruptions are unlikely in the near future.

Holocene Mount Rainier: Alteration, Eruption, and Edifice Collapse

The Osceola Mudflow of 5.6 ka was the signature event in the Holocene history of Mount Rainier. During a period of eruptions, the volcano's summit and northeast slope fell away, creating a ~1.8 km-wide horseshoe-shaped crater, open to the northeast. The collapsed material is remarkable for its volume (~3.8 km^3), abundance of hydrothermal clay, and its nearly immediate transformation to mobile lahar. Scott et al. [1995] and Vallance and Scott [1997] clarified understanding of the Osceola event by showing that the leading portion of the Osceola lahar derived from the more coherent and less altered outer carapace of the volcano and formed a proximal hummocky deposit previously known as the Greenwater lahar. The more clay-rich interior and summit portions of the edifice formed the more mobile Osceola Mudflow facies that reached to Puget Sound. Subsequent eruptions have largely filled the Osceola collapse crater.

By carefully documenting ages and inundation limits of post-Osceola lahars, Scott et al. [1995] constructed hazard maps for river valleys heading on Mount Rainier. These maps show areas likely to be inundated by lahars of three categories of increasing magnitude and decreasing frequency of occurrence. Utilizing these maps and supporting information, Iverson et al. [1998] developed a general method of forecasting lahar inundation areas for volcanoes.

Several other far-reaching Holocene lahars from Mount Rainier also contain clays and

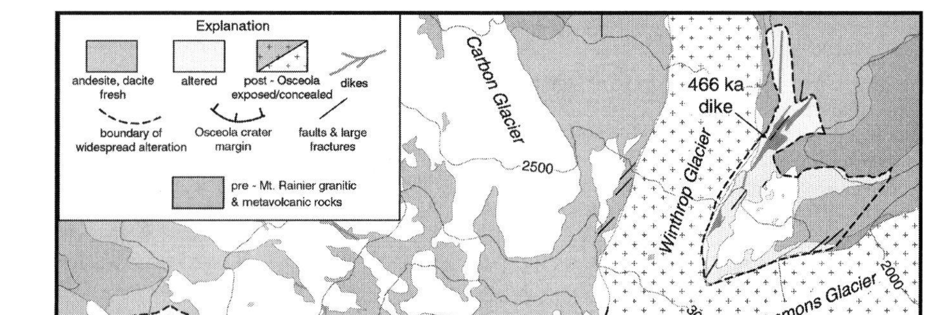

Fig. 3. Simplified geology of upper Mount Rainier showing mapped dikes (red) and fractures (T. W. Sisson, unpublished data, 2000) and areas of weakly through intensively hydrothermally altered rocks (yellow) [Zimbelman, 1996; Crowley and Zimbelman, 1997; and Sisson, unpublished data, 2000]. Cross pattern shows area underlain by post-Osceola volcanic rocks. Glaciers heading on the altered western flank drain into the Puyallup River system. Original color image appears at the back of this volume.

other hydrothermal minerals, and clay-rich altered portions of the volcano appear to have collapsed preferentially. The image of an unstable edifice composed of widespread weak altered rocks "stewing in its own juices" was seized upon quickly by the popular press. In actuality, detailed geologic mapping, remote sensing [*Crowley and Zimbelman*, 1997], and geochronology establish that intense and pervasive alteration of argillic and advanced argillic type is confined to a relatively narrow east-northeast-west-southwest trending belt that passes through the summit (Figure 3). The summit and upper eastern portion of this belt failed during the Osceola collapse. Flank alteration was driven by emplacement of radial dikes that lace the altered belt [*Zimbelman*, 1996] but that are scarce on the generally alteration-free north and south flanks of the edifice. The strong localization of radial dikes was likely inherited from similar-trending, pre-existing fractures in the sub-edifice Tertiary basement that are perpendicular to regional folds. The largest and most abundant radial dikes intruded during the two Middle Pleistocene periods of high effusion (Figure 2) and their associated alteration is fossil, not ongoing. In contrast to the altered belt, the dominant unaltered portions of the edifice have been surprisingly stable, as is shown by widespread preservation of rocks as old as 200 ka above 4200 m elevation on the volcano's northwest face.

Important questions remained about the distribution of altered, structurally weak rocks and their consequences for collapse hazards. Young lavas have nearly filled the northeast-facing Osceola collapse crater (Figure 3), and it was unknown if weak, altered rocks widely underlie these or if collapse removed most weak material from beneath the volcano's summit and upper northeast slope. Portions of the new summit craters are also highly altered, and young alteration may have extended to deep within the volcano's core. High-resolution aeromagnetic and electrical resistivity surveys help to assess the extent of structurally weak, highly altered rocks on the upper edifice [*Finn et al.*, 2001]. Magnetic anomalies show that large volumes of highly altered rock are restricted to the volcano's upper west flank and to smaller bodies in the subsurface that partially ring the Osceola collapse crater. Very small amounts of extremely altered rock underlie the volcano's summit and upper northeast slope.

The effect of alteration on edifice failure has been assessed with three-dimensional slope stability models incorporating measured rock properties and probable distributions of fresh, weakly altered, and intensely altered rock [*Reid et al.*, 1999; *Watters et al.*, 2000]. Evaluation of millions of potential failure surfaces yielded relative stability maps of the edifice. Assessments based on both liberal and conservative distributions of intensely altered rock identify Mount Rainier's upper west flank as having the greatest likelihood of gravitational failure, consistent with the history of post-Osceola, alteration-bearing lahars. Collapse-generated lahars pose the greatest risk to the Puyallup River valley that heads on the volcano's altered west flank.

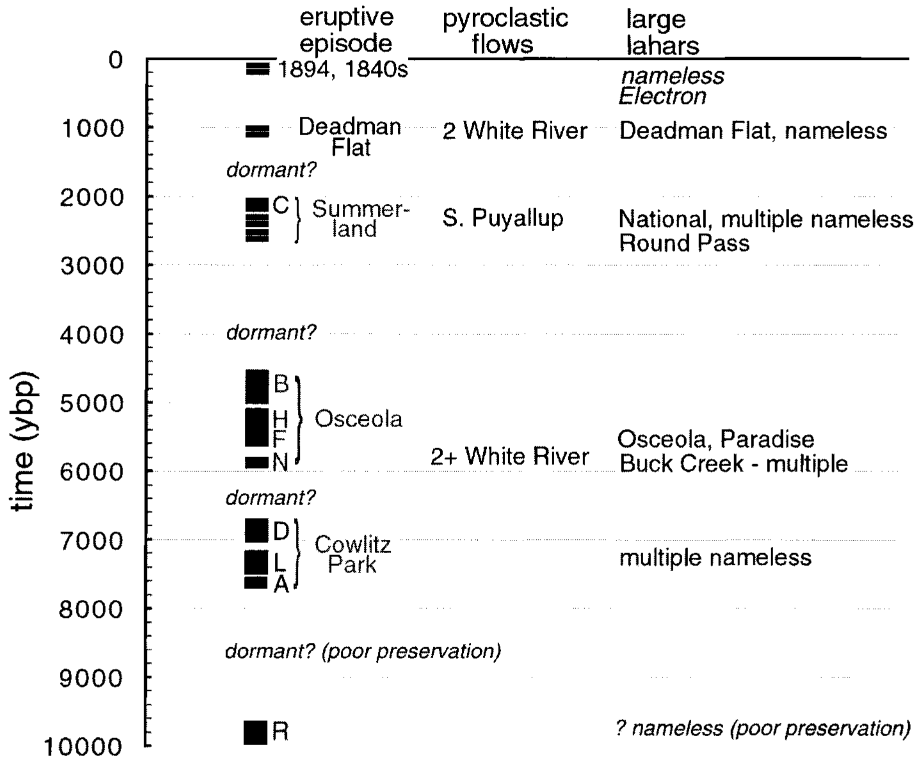

Fig. 4. Holocene eruptions and major lahars (>20 km long) from Mount Rainier. General eruptive periods (black bars) and named ashes (C, B, F, etc.) from USGS reports plus Vallance and Donoghue (unpublished); lahar ages from Scott et al. [1995] and K. Scott (personal communication, 2000). Italics denote lahars outside known eruptive periods.

J. Vallance and S. Donoghue re-examined Mount Rainier's Holocene ash record to better determine eruptive frequency and style, and to assess possible links between eruptions and lahars. They find that, in addition to 10 previously identified pumiceous tephras, there are numerous thin, dark, poorly vesiculated glassy ashes that were probably deposited during phreatomagmatic eruptions and pyroclastic flows. The inconspicuous, thin deposits had been noted by earlier workers but had not been positively identified as ash and correlated within the volcano's Holocene tephra section. The poorly vesiculated ashes establish that eruptions were at least twice as frequent as the pumiceous tephras had indicated. Tephras cluster into eruptive periods that coincide with large and frequent lahars (Figure 4), suggesting that eruptions trigger lahars, either directly, when hot rock avalanches and pyroclastic flows sweep across snow and ice, or indirectly when volcanic unrest dislodges unstable edifice flanks. Spontaneous, unheralded collapses of volcano flanks appear less common than was previously supposed, and pre-eruptive seismicity, enhanced gas emissions, or edifice deformation may precede and warn of future large lahars. An exception may be the alteration-rich Electron Mudflow of ~560 y B.P., for which no evidence of an associated eruption has yet been found.

Thin ashes need not signal inconsequential eruptions, as is shown by a thin, 1100-year-old ash that is restricted to valleys at the northeast foot of the volcano. Large lahars inundated the downstream valleys at this time, and their runout floods may have carried sediments as far as the present Port of Seattle, where P. Pringle and co-workers have traced ~1100-year-old ash-rich sand.

Mount Rainier and its vicinity are seismically active with seismicity concentrated both at the edifice and to the west in a broad north-south belt known as the west Rainier seismic zone (WRSZ, Figure 1). Frequent seismicity raises concerns that edifice-centered earthquakes might result from ongoing disintegration of the volcano and that the WRSZ or other sources might produce earthquakes severe enough to trigger edifice collapse. Additional seismic stations were installed to monitor the volcano, and Moran et al. [2000] show that nearly all edifice-centered earthquakes originate beneath the base of the volcano atop a 10-km-thick region of low seismic velocity that is interpreted to be nearly solidified small magma bodies and hydrothermally altered rocks. Edifice-centered seismicity probably results from active hydrothermal processes in sub-edifice basement instead of edifice disintegration. WRSZ earthquakes are most consistent with a network of relatively short faults at angles to the trend of the seismic zone, and the probable maximum magnitude is ~5.5, not the potential magnitude 7 that could be anticipated if the zone were a single long fault. These conclusions reduce, but do not eliminate, concerns for edifice collapse triggered by local or regional seismicity.

Hazards Outreach and Community Response

A primary benefit of Mount Rainier's INDNR Decade Volcano designation has been capturing the attention of the press and local officials, thereby aiding public education and development of hazards response plans. Residents of the Pacific Northwest accept that Cascade volcanoes erupt and that their eruptions can be enormously powerful and destructive because of the example of Mount St. Helens. Mount Rainier hazards information is disseminated in multiple formats including fact sheets, displays, a video, a teacher's activity package, lectures and interviews, and the Internet (http://vulcan.wr.usgs.gov). The National Park Service incorporates volcano hazards information in their displays and presentations to Park visitors and posts hazards information at potentially threatened sites in Mount Rainier National Park.

Heightened concern led to formation of a Mount Rainier Volcano Hazards Working Group that coordinates efforts of local, county, state, and federal officials in developing and implementing volcanic emergency response plans. The working group's response plan includes signed evacuation routes, evacuation procedures, and information for threatened facilities and communities. The working group is also implementing a pilot lahar-warning system comprising a series of telemetered geophones to detect lahars on the Puyallup and Carbon Rivers that head on the volcano's west and north slopes and sirens to warn the endangered communities. Lahar-hazard boundaries, zoning districts, roads, and public facilities are displayed on Pierce County's Web site: http://triton.co.pierce.wa.us.

Substantial progress has been made in understanding Mount Rainier's volcanic hazards and their causes. Collapse hazards are greatest on the west flank for simple geologic reasons, and edifice stability modeling promises to quantitatively assess collapse risks. At the same time, the likelihood of lahars formed by magma-ice interaction chiefly by pyroclastic flows is higher than was previously supposed, and such eruption-generated lahars threaten all valleys that head on the volcano. Mount Rainier has erupted more frequently than was previously known, and links between eruptions and lahars, including flank-collapse lahars, are stronger than had been thought. In such situations, seismic and other eruption precursors could allow communities to go to a heightened level of alert and take basic precautions against lahars. Some sizeable lahars have no known eruptive triggers, and unheralded flank-collapse lahars could possibly challenge hazards response planning.

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Hunting and Gathering Silicon Data to Tackle Climate Forecasting

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The frequent, large, and often extremely abrupt shifts in global climate in the past occurred in lockstep across the globe. This seems to tell us that Earth's climate system has several distinct modes of operation that are linked in subtle yet dramatic ways.

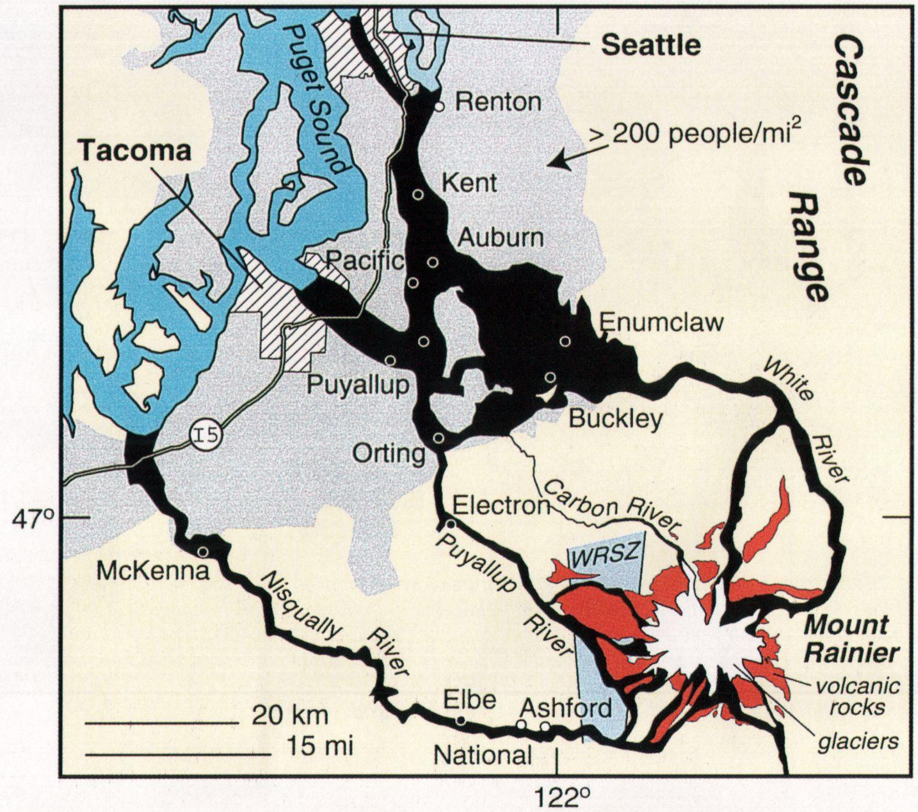
Does this finding about past climates have any implication for future climate? Will greenhouse warming continue, or will it slow or cease? And when would that be?

For decades, marine scientists and modelers have tried to understand the interdependencies between climate change and the carbon cycle, particularly those associated with variations in the atmospheric CO_2 concentration. Predictions about future climate change are derived by modeling the marine biogeochemical cycling of carbon and associated biogenic elements. A suite of global climate models that can reproduce our present-day climate already exist.

However, those of us involved with the SINOPS project (see Acknowledgments) believe that, for realistic prognostic scenarios, it is essential that the models reproduce climatic changes qualitatively as well as quantitatively. The only way of testing this ability lies in attempts to reconstruct present and past climates, as well as the oceanic distribution of biogeochemical tracers with these models (Figure 1). The validity of those tests, however, depends crucially on the quality of the existing oceanographic, sedimentological, etc. data sets. When both model and data base are as competent as possible, they can diagnose each other's deficiencies systematically, remove disagreements, and develop new parameterizations that may help the scientific community solve the mystery of climate change. With this publication, we solicit all scientists to submit data to improve this data base.

Why, of all things, the silicon cycle? There are four reasons for focusing on the silicon cycle: 1) Diatoms are the major contributors to the global biogenic opal (that is, biogenic silica, BSi) production and they account for about half of global marine organic carbon production [*Nelson et al.*, 1995]. 2) Diatoms contribute even more to the export of organic carbon to the deep sea; thus, they play a key role in the biological pumping of the greenhouse gas CO_2 down to the deep sea [e.g., *Buesseler*, 1998]. 3) The availability of silicic acid has been hypothesized to control diatom productivity [e.g., *Dugdale and Wilkerson*, 1998] and to have a strong impact on the global carbon cycle and the climate evolution by controlling the organic carbon biological pump efficiency [e.g., *Ragueneau et al.*, 2000]. 4) Three percent of the total BSi produced in surface waters gets buried in the sediment [*Tréguer et al.*, 1995] compared to 0.04 – 0.1% for organic carbon [*Emerson and Hedges*, 1988; *Westbroek et al.*, 1993].

Given the good preservation efficiency of BSi and the importance of diatoms in the global carbon cycle, sedimentary BSi mass accumulation rate (MAR) and diatom assemblages represent unique paleoceanographic tracers. BSi MAR can be used as a proxy of paleoproductivity while diatom assemblages can be used for paleoenvironmental



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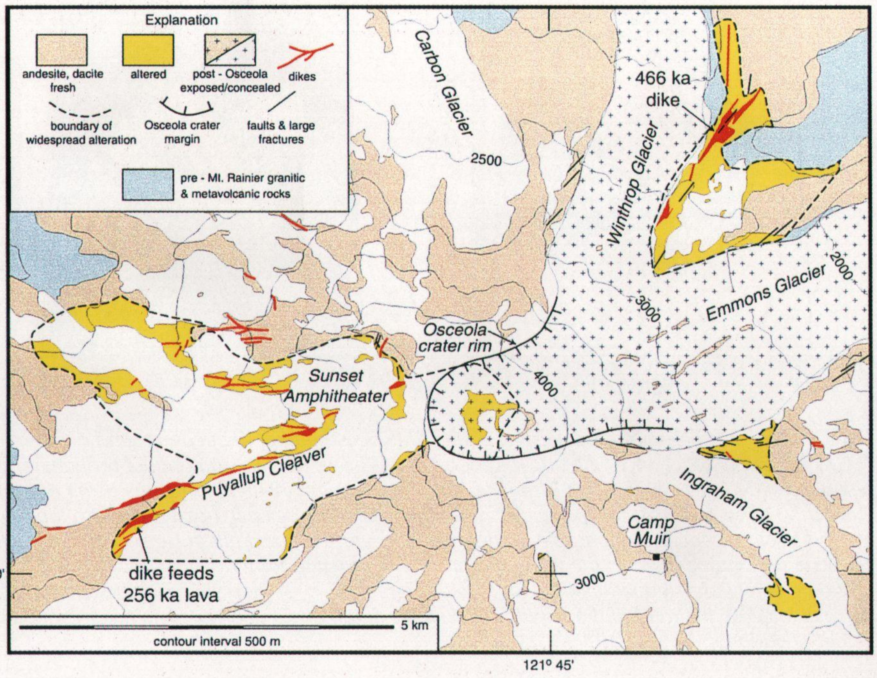

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