RECLAMATION ISSUE

- Flood plains, salmon habitat, and sand and gravel mining, p. 3
- Reclamation of flood-plain sand and gravel pits as off-channel salmon habitat, p. 21
- Innovations and trends in reclamation of metal-mine tailings, p. 29
- Surface Mine Reclamation Awards, p. 43
- Early Miocene trace fossils from southwest Washington, p. 48
- Radiocarbon ages of probable coseismic features from the Olympic Peninsula and Lake Sammamish, Washington, p. 59
- Notes on the new Washington State fossil, *Mammuthus columbi*, p. 68
Division of Geology and Earth Resources

Raymond Lasmanis, State Geologist
J. Eric Schuster, Assistant State Geologist
William S. Lingley, Jr., Assistant State Geologist

Geologists (Olympia)
Joe D. Dragovich
Wendy J. Gerstel
Robert L. (Josh) Logan
David K. Norman
Stephen P. Palmer
Patrick T. Pringle
Katherine M. Reed
Henry W. (Hank) Schasse
Timothy J. Walsh
Weldon W. Rau (volunteer)

Geologists (Spokane)
Robert E. Derkey

Geologists (Regions)
Garth Anderson (Northwest)
Charles W. (Chuck) Gulick (Northeast)
Rex J. Hapala (Southwest)
Lorraine Powell (Southeast)
Stephanie Zurensko (Central)

Senior Librarian
Connie J. Manson

Library Information Specialist
Lee Walkling

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DIVISION OF GEOLOGY AND EARTH RESOURCES

Raymond Lasmanis, State Geologist
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Stephanie Zurensko (Central)

Senior Librarian
Connie J. Manson

Library Information Specialist
Lee Walkling

MAIN OFFICE
Department of Natural Resources
Division of Geology and Earth Resources
PO Box 47007
Olympia, WA 98504-7007
Phone: (360) 902-1450
Fax: (360) 902-1785
(See map on inside back cover for main office location.)

Internet Connections:
Library inquiries:
connie.manson@wadnr.gov
lee.walkling@wadnr.gov
Subscriptions/address changes:
geology@wadnr.gov
URL: http://www.wa.gov/dnr/htdocs/ger/ger.html

FIELD OFFICE
Department of Natural Resources
Division of Geology and Earth Resources
904 W. Riverside, Room 209
Spokane, WA 99201-1011
Phone: (509) 456-3255
Fax: (509) 456-6115
E-mail: robert.derkey@wadnr.gov

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Cover Photo: The East Fork Lewis River, Clark County, southwest Washington, in June 1994. Ponds created by gravel mining here cover approximately 200 acres on both sides of the river and are about 30 ft deep. The valley is approximately 1 mile wide in this area. During 1995 and 1996, the river avulsed through a gravel pond (shown by solid line) and abandoned about 1,700 ft of channel. Later avulsion forced the river into the lower gravel pits and abandoned an additional 3,200 ft of channel. Small arrows indicate the 1994 path of the river (today’s abandoned channel). See related article, p. 3.


State Geologist Ray Lasmanis with Washington STATEMAP poster.

Association of American State Geologists Present Results of STATEMAP Program

Raymond Lasmanis, State Geologist
Washington Department of Natural Resources
Division of Geology and Earth Resources
PO Box 47007, Olympia, WA 98504-7007

On March 18, 1998, the Association of American State Geologists hosted a reception in the foyer of the Rayburn House Office Building in Washington, D.C. Members of Congress and their staff, committee staff, and representatives of agencies that use geologic maps were invited guests. Forty-five state geologists participated, and each state presented a poster displaying a STATEMAP product and derivative information that addresses societal needs.

I presented the poster for Washington State. It consisted of two derivative maps derived from a digital version of the 1:100,000-scale Seattle quadrangle. Developed using Depart-
INTRODUCTION

People who live or work along rivers and their flood plains know these are hydrologically and biologically dynamic environments. Rivers flood and shift their courses from time to time, resulting in natural cycles of erosion and deposition of sand and gravel. The river and its banks are also home to many fish and wildlife species. In this age of rapid land development, however, people have turned to rivers (dredging and gravel bar mining) and flood plains (gravel pit lakes) as sources of sand and gravel for construction aggregates.

Gravel mining practices such as channel dredging are typically done with either a dragline or suction dredge (Fig. 1) and are conducted mostly in the Columbia River, where a shipping channel is maintained, and the Cowlitz River, where large volumes of sediment from the 1980 Mount St. Helens eruption are still being deposited. Gravel bar mining (scalping) (Fig. 2) is performed in many Washington rivers for aggregate and in an attempt at flood control (Collins, 1996). Miners no longer dig into the banks of rivers (Fig. 3). Also, the Army Corps of Engineers, state agencies, and some local governments have recognized the environmental effects of in-stream mining. The Grays Harbor County Planning Department, for example, has mandated reduced rates of gravel removal on the Satsop, Wynoochee, and Humptulips Rivers (Collins and Dunne, 1990). (See Fig. 6.)

Flood-plain mining, digging gravel pit lakes adjacent to rivers, is a common activity in Washington. “Flood plain” as defined in Washington’s Shoreline Management Act (Revised Code of Washington [RCW] 90.58) means the 100-year flood plain, the area susceptible to flooding by a stream for which there is a one percent chance of inundation in any given year (Washington Department of Ecology, 1994). The 100-year flood plain definition must be used with caution because the small flood-frequency data sets result in large potential for error in identifying the 100-year event and determining the area affected (Mount, 1995). Also, as watersheds become more developed and roofs and roads present large areas of impermeable surfaces, high-intensity peak runoff occurs more frequently and with greater volume (Booth, 1991). The definition of the 100-year flood plain is important in Washington because most regulation of development and mining depends on where this “line” is drawn. Furthermore, the geomorphic flood plain, or the area where fluvial erosion has created a flat valley, is generally much larger than the “calculated” 100-yr flood plain and is where mining occurs.

Flood plains support diverse plant and animal populations, as well as much of our agricultural system (Teskey and Hinkley, 1977). Vegetation along river banks provides habitat for most wildlife. Significantly, the riverine environment is home to the many species of Pacific salmon (*Oncorhynchus* sp.) indigenous to Washington (Palmisano and others, 1993; Washington Department of Fish and Wildlife, 1997; Sedell and Luchessa, 1982). The riparian area is where aquatic and terrestrial ecosystems interact and is essential to both fish and wildlife. Streamside plants shade the water, help moderate water temperature, and promote stream-bank stability, as well as providing the organic nutrient load in the aquatic ecosystem. These plants are the source of large in-stream woody debris that provides refuge and food sources (Washington Department of Natural Resources, 1996). Salmon use gravel channels for spawning and clay-bottom channels, with their rich subaqueous flora, for overwintering, feeding, and refuge. Side-channels (yazoo tributaries) and oxbow lakes are types of wallbase channels (Fig. 4A) or off-channel sites that are primary overwintering habitats for juvenile coho salmon and cutthroat trout (Peterson, 1980; Cederholm and Scarlett, 1981; 

![Figure 1. A suction gravel dredge and barges at work in the Chehalis River in the mid-1960s. This type of mining now occurs chiefly in the Columbia and Cowlitz Rivers to remove sediment deposited after the Mount St. Helens eruption. Note the suspended sediment plume moving downstream. (Photo by Lloyd Phinny, Washington Department of Fisheries.)](image-url)
Peterson and Reid, 1984; Cederholm and Scarlett, 1991). Wallbase channels commonly look like swamps, ponds, or small tributaries and are connected to the main stem of the river by a small stream called an ingress/egress channel.

Rivers in Washington generally have steep gradients and V-shaped cross sections in their upper reaches. Headward erosion occurs where stream gradients rapidly steepen, as in the Olympic and Cascade mountains. As the rivers approach the ocean or find their way across the Columbia Basin, gradients decrease, valleys broaden, flow velocity decreases, and gravels are deposited. Deposition is greatest at the gradient changes. The river accommodates this aggradation by lateral (horizontal) migration. Traces of channel shifts and stream meanders are common flood-plain features; oxbow lakes and side channels are testament to the history of this activity (Fig. 4A,B).

Flood-plain gravel mining generally occurs where the gravel bedload has been deposited, for example, at gradient changes or above or below topographic constrictions through which a river flows (such as Union or Selah gaps on the Yakima River). In Washington, many gravel pits near rivers have been excavated for fill material for major highway projects, a process that further complicates flood-plain functions. Examples are I-90 along the Yakima River, I-5 where it crosses the Skookumchuck River at Centralia, I-82 near metropolitan Yakima on the Yakima and Naches Rivers, and in several places along the East Fork Lewis River near Vancouver. Gravel sources located near the point of use significantly reduce the cost of the aggregate.

Seeking the lowest cost material, gravel miners commonly choose to excavate large, deep ponds adjacent to active river channels (Fig. 4A). These pits have the potential to significantly change the physical and ecological function of flood plains (Collins, 1996, 1997). Wherever a channel shifts into a gravel pit or multiple pits that are large relative to the scale of the flood plain and the river’s sediment transport regime, natural recovery of original flood plain environment and similar channel morphology could take millennia (Collins, 1997). The time for recovery is highly dependent on the availability of sediment, particle size, gradient, and the size of excavations to be filled.

Regardless of the best planning and intentions, impacts of flood-plain mining may simply be delayed until the river is captured by the gravel pit. While capture may not occur in the next 100-year flood event, it is likely to occur in the future as development and consequent flood magnitude increase. In the long term, stream capture by gravel pits is a near certainty. Because the gravel pits have a lower base elevation, there is risk of rapid channel change into the pits during high flows, a process termed avulsion. The flooded pits “capture” the stream. The effects of avulsion are similar to those of in-stream mining discussed in Evoy and Holland (1989), Collins and Dunne.
(1990), Netsch and others (1981), Kondolf and Graham Matthews (1993), Kondolf (1993, 1994), and Williamson and others (1995a,b). They may include:

- lowering the river bed upstream and downstream of mining operations, causing river bed erosion and (or) channel incision and bank erosion and collapse,
- eroding of footings for bridges or utility rights-of-way,
- changing aquatic habitat,
- unnaturally simplifying the complex natural stream system,
- increasing suspended sediment, and
- abandoning reaches of spawning gravels or damaging these gravels by channel erosion or deposition of silts in spawning and rearing reaches.

Flood-plain mine lakes, the loss of natural flood-plain habitat, and the isolation of the flood plain from its river byarmor and dikes that protect against avulsion are semipermanent consequences of flood-plain mining. Careful reclamation may restore some of the previous function of a flood plain; however, it may be impossible to replace lost habitat in the near term if a substantial amount of a flood plain has been converted to pit lakes (Collins, 1996, 1997).

Careful siting, planning, limiting mining, a thorough hydrogeological analysis, use of alternative resources, and innovative reclamation can mitigate and reduce some mining impacts. This article describes river processes and mining operations and discusses some examples of flood-plain mines. Reclamation of these mines is the subject of the article by Norman (this issue, p. 21).
FLOOD-PLAIN HYDRAULIC PROCESSES

Many Washington river valleys reflect millions of years of fluval processes and in some places modification by glaciers. Most lowland river valleys are filled with alluvial sand, gravel, silt, and clay, which have been spread out across the adjacent vegetated flood plains wherever flood flows have left the main channel. Small irregularities in the channel cause local variations in flow velocity, which in turn contribute to variations in erosion and sediment deposition. From these variations, the river begins slow lateral displacement, depositing on one stream bank while eroding, scraping, and undercutting the other bank as it gradually migrates from side to side across its valley floor. The valley widens over time by erosion, particularly on the outside of river bends and where the flow impinges against the valley walls. The river’s course appears snake-like when viewed from above (Leopold and others, 1964).

The water strikes with greatest force against the outer (concave), downstream bank of the meander bend, causing erosion. Flow is slower on the inside (convex) bank of a meander where deposition occurs. These deposits are called point bars, gravel bars, or lateral accretion surfaces. Over time, meanders can enlarge sideways and shift downstream by a combination of erosion and sedimentation processes. A meandering river generally retains the same approximate channel width, but a given river channel may eventually occupy most parts of a flood plain throughout its geologic history (Fig. 4A,B).

Meander bends do not enlarge indefinitely because they become sizable detours for the flowing water. Eventually, the river will cut off a meander and abandon the longer, curved channel for the shorter, more direct route. The cutoff meander sections are termed oxbows. Where they are filled with water, they are called oxbow lakes or ponds (Fig. 4A,B). Meander cutoffs most commonly occur during floods, when large volumes of water have enough additional momentum to carve the shortcut and bypass the meander bend.

As river profiles or individual reaches become stable over a period of years, they achieve a balance between erosion and deposition. At equilibrium, the river or a reach is a graded stream, one in which the slope, velocity, and discharge combine to transport its sediment load with neither erosion nor sedimentation (Mackin, 1948). That balance is governed by the elevation of its base level (for example, an adjacent ocean or lake level) and the many physical and biological factors that control equilibrium. Base levels and the stream’s equilibrium profile can be altered by human intervention, such as dam building, activities that cause river avulsion, or removal of gravel bars. Gradually the stream’s profile will reach a new equilibrium, but this may change the distribution of erosion and deposition sites and also the shape of the channel.

A flood plain is a flat or gently sloping region along a stream channel, typically extending laterally to the adjacent slopes, onto which the stream expands during floods (Fig. 4A,B). With time, lateral erosion associated with meandering, channel sediment deposition, and additional overbank sedimentation during floods combine to create a flood plain. The width of the flood plain is a function of many factors, including the size of the stream, relative rates of meander migration and downcutting, and the ease with which the valley walls are eroded. During periods between floods, the meandering stream occupies only a portion of the breadth of the flood plain. Slow lateral channel migrations over long periods of time tend to maintain a single flood plain with a fairly level surface. In aggrading reaches, where cobbles and boulders are the dominant bedload and sediment transport rates are high, the river may take on a braided morphology. Braided rivers are characterized by a channel dividing and reuniting in an intricate interlaced fashion. Early maps of the state show that many rivers flowing from the Cascades had braided channels.

If conditions are suddenly and significantly changed, relative rates of meandering and downcutting may accelerate, and the old flood plain may be cut up by development of new, narrower channels. Incision can result from an increase in the river’s discharge, reduction in the size of its bedload, dredging, avulsion into a gravel pit, or upstream levee construction.

As a valley widens, the stream’s flood plain also widens. The flood plain width can be limited, as it is along the entrenched Yakima River canyon between Ellensburg and Roza dam (Figs. 5, 6), or very broad, as it is along the Chehalis River downstream of Oakville, where it is more than 2 mi wide (Waitt, 1979; U.S. Army Corps of Engineers, 1970). A flood plain’s width can also be out of proportion to its river channel. For example, the Chehalis River appears to have an undersized channel in the wide valley along its lower reaches. During the Pleistocene epoch, the Chehalis River valley was the outlet for the enormous amounts of glacial outwash and meltwater from the Puget ice lobe (Bretz, 1913; Eddy, 1966). The modern Chehalis River drains a much lower and smaller watershed area. The upper reaches of rivers such as the Stillaguamish, Cowlitz, and east fork of the Lewis (Mundorff, 1984) flow in more restricted glacier-carved valleys; only in the lower parts of these valleys do they appear underfit in proportion to their overall flood-plain size.

Figure 5. Yakima Canyon near Umtanum gaging station; view to the north, toward Ellensburg. Note the entrenched river with meander loops cut into the basalt flows. The resistant basalt constrains the channel, and no flood plain can develop here, and no off-channel habitat can be created as on a flatter flood plain.
**BIOLICAL PROCESSES IN FLOOD PLAINS**

**Off-Channel Habitat for Salmon**

Rivers are not isolated ribbons of water flowing through a valley; they are connected to their valleys and flood plains by both surface water and shallow ground-water sources (Collins, 1996). Wallbase channels (Fig. 4A, B) form on flood plains where runoff reoccupies abandoned channels created by the migration of main stem rivers (Peterson and Reid, 1984). Wallbase channels develop along meander scars and oxbows or behind gravel bars; in most places they appear as swamps, ponds, or small tributaries and are connected to the main stem (Fig. 7).

During spring and fall, juvenile salmon migrate out of main rivers into tributaries, including wallbase channels, where they seek refuge from high flows and turbidity for varying periods of time (Cederholm and Scarlett, 1981; Peterson and Reid, 1984; Peterson, 1982; Scarlett and Cederholm, 1984; Brown and Hartman, 1988). In fall, these movements are initiated during the first freshet (Peterson, 1980). Increased discharge and turbidity in the main river relative to clear water flowing from wallbase channels attracts large numbers of juvenile coho and cutthroat. While in these channels, salmon take advantage of a rich food supply of aquatic insects and relatively stable hydrological conditions. Juvenile salmon typically feed in the shallows and seek cover from predators in deeper water or in woody debris complexes and emergent vegetation. The growth that the juvenile salmon immigrants (Fig. 8) are able to acquire in these habitats improves their overall size and survival rates (Peterson, 1980; 1982).

Poorly planned mining exposes these salmon habitats to potential avulsion. Many gravel pit mines have been established in active wallbase channels, sloughs, and (or) marshes (Collins, 1996, 1997), resulting in destruction of salmon habitat. In rare instances, flood-plain mining has created effective off-channel habitat (see Norman, this issue, p. 21).

**Benthic Insects and the Hyporheic Zone**

Benthic macroinvertebrates are an important food source for juvenile salmon (Mundie 1969). Many benthic invertebrates, such as caddis flies, mayflies, and stone flies, spend all or part of their lives in a clean gravelly substrate that has abundant oxygenated water (Pennak 1978; Merritt and Cummins, 1984). Healthy streams are characterized by a high species diversity of benthic macroinvertebrates and a moderate number of individuals of any given species group (Brookes, 1989). Unhealthy streams, on the other hand, are characterized by low species diversity and large numbers of individuals in any species group.

The hyporheic zone (Fig. 4A), the shallow unconfined aquifer under the flood plain that is in hydraulic continuity with the river, may extend miles horizontally across the width of the flood plain and many yards beneath the surface (Stanford and Ward, 1988). This zone provides extensive interstitial (intergranular) habitat for benthic macroinvertebrates. The hyporheic zone serves as a refuge for benthic insects during droughts and high-flow events, and it is capable of re-supplying the population of an area at and immediately below the stream bed once conditions in the stream improve. This zone plays a major ecological role in streams, especially those...
that have coarse substrates where most aquatic insects spend important parts of their life cycle (Ward, 1992). Overly large and deep flood-plain mines may significantly interrupt local hyporheic processes through removal of gravels and (or) by changing water-table elevations.

**Effects of Avulsion**

Salmon depend on a river system that functions well. Salmon lay their eggs in gravels, where cool, oxygenated water flows freely over the eggs, assuring their normal development. Generally, the most productive river substrates are those that are stable and have a wide range of particle sizes. They also produce the most diverse invertebrate populations (Brookes, 1989). If the gravel substrate is disturbed or is filled and covered by silt and clay, as can happen during floods and avulsion episodes, salmon egg nests (redds) can be eroded away or smothered. Additionally, the benthic invertebrate community is likely to change and become less productive when the stream bed is altered. Where velocities are persistently high, many kinds of benthic macroinvertebrates may be absent.

When a river breaches a pit, the river biota can be catastrophically changed. Water temperatures may rise during summer and early fall because the relatively slack water in the pits is exposed to sunlight for long periods. Water temperatures above 75°F may be fatal to some salmon species, and temperatures between 60° and 75°F can increase their metabolic rates and stress levels. While moderate increases in water temperature can increase growth rates, large increases can cause disease outbreaks and may kill significant numbers of adult and juvenile fish (Bjornn and Reiser, 1991).

Pits that are warmer than the adjacent river may be ideal habitat for warm-water fish, such as large mouth bass or yellow perch, which are predators of juvenile salmon (Kondolf and others, 1996). This may be particularly applicable in the lower reaches of the Yakima River, where low flows and warming river water during summers is a chronic problem. Additionally, smolting juvenile salmon may become disoriented in the quiet waters of a pit that has been captured by a river (Ken Bates, Washington Department of Fish and Wildlife [WADFW], written commun., 1998).

**RIVERS AND FLOOD PLAINS AFFECTED BY MINING IN WASHINGTON**

Flood-plain mining has occurred on many rivers in Washington State and is highly concentrated along the Yakima River.
and its tributaries (Naches and Cle Elum Rivers), the Chehalis River and its tributaries (Wynoochee, Satsop, Newaukum, and Skookumchuck Rivers), and the Cowlitz River and East Fork Lewis Rivers (Fig. 6) (Collins, 1996, 1997). Collins estimates that about one-sixth of Washington’s gravel production was removed from riverine sources between 1970 and 1991, and most of this mining was located on flood plains and active gravel bars. However, this paper does not attempt to address all the flood-plain gravel pits in the state.

Many currently permitted mines cover several hundred acres of flood plain that have been excavated or are scheduled for excavation. The depth and size of many of these mines was restricted by economics and the types of machinery used.

Gravel mining has created pit lakes ranging from a few acres to several hundred acres and with depths averaging about 30 ft. Several mined lakes are as deep as 90 ft, and some are as much as five times as deep as the adjacent river. Some of these deep lakes are within 50 ft of the active river channels. This head differential makes them highly vulnerable to river avulsion during high flows. Rivers have avulsed at several mines in Washington (see Table 1) in the last 14 years, most of them during storms in 1995 and 1996.

Some Effects of River Diking and Channelization

Mining in depositional reaches commonly occurs on both sides of a river (for example, mines on the north and south banks of the East Fork Lewis River). The typical method of attempting to prevent a river from flooding a pit is armoring the active channel bank with riprap or building dikes and levees. Where bank armoring and dikes tend to minimize lateral erosion, they may reduce the supply of sand and gravel to the active channel and prevent maintenance or creation of habitat diversity in both the main stem river and side channels.

Channelization using bank armoring and dikes attempts to confine the river to one main channel and prevent it from migrating across the flood plain. Channelization can smooth and (or) straighten a channel, a process that reduces energy dissipation and moves channel and bank instability and flooding problems (as well as increased sediment load) to downstream reaches. When the channel or thalweg (the deepest part of the channel) is moved or deflected by levees or dikes, the realignment may temporarily affect the downstream channel and banks as the thalweg scours through salmon spawning habitats or impinges on channel banks (WADFW, 1998).

Channelization can change flow velocity and the substrate, which may change benthic macroinvertebrate populations on which fish depend for food (Brookes, 1989). Additionally, where armoring interferes with natural meander patterns, any deposition will be confined to the active channel. Sediment may have to be removed on a regular basis just to maintain channel depth and flow capacity (Brookes, 1989). Gravel buildup in channelized rivers can result in the river being perched above adjacent flood plains—and the adjacent gravel pits—and making it prone to avulsion.

Some levees (also called flood berms) that are used to protect gravel pits from flooding and avulsion are composed of materials originally carried by the river to the pit site. The materials are, therefore, of a size that the river can easily transport. These dikes can be washed away during a flood or gradually made porous as fines are washed out. Through this washing process a levee can become a windrow of unconsolidated gravel that is highly vulnerable to collapse. Channel migration and single-event bank failures reduce the width of the dike and weaken it.

Additionally, dikes and levees can be damaged by dewatering an adjacent pit by pumping or flow through an outlet channel. During floods, when the river’s level is abnormally high, a large static head exists between the higher river water surface and that of the pit. Here, the potential for dike collapse and avulsion is great. The dikes are weakened by the constant head difference. Floods that overtop dikes can allow a river to rapidly cut through these structures as the flow drops from the river surface into the pit, causing headward erosion. In effect, dikes and levees are only short term solutions to long term natural processes such as channel migration and flooding.

Consequences of River Avulsion

Typically, avulsion occurs during floods. Avulsion is characterized by a sudden change in the course of a river that causes it to break through a low point such as a meander neck (to form an oxbow lake) or to rush into a gravel pit. Avulsion events occur in gravel pit lakes because the pit surface is lower than the river. The old river channel can be partially or completely abandoned in the avulsion process.

Pits are typically wider and deeper than the river (Fig. 4A) and out of proportion to the overall scale of the river (Collins, 1997; Woodward-Clyde Consultants, 1980a,b). The severity of the consequences of breaching a pit depends on the relative scale of the mining operation and the river. Significant amounts of material must be moved from the river bed and banks to fill a deep pit.

Once avulsion and breaching begin, the knickpoint, where the river enters the pit (Fig. 9), immediately moves upstream, and the riverbed starts to be scoured (Kondolf, 1993; Kondolf and others, 1996; Collins and Dunne, 1990; Collins, 1996, 1997). This scouring cuts downward and lowers the river elevation, a condition called incision. Avulsion into gravel pits by the Clackamas River at Clackamas, Oregon, in February of 1996 resulted in incision of more than 2 yards over a distance of one-third of a mile upstream of the pit (Kondolf and others, 1996). Hazardous consequences of this kind of erosion can be undercutting of levees, bridge supports, pipelines, and utility towers and other structures. For example, when a gravel pit on the alluvial fan of Tujunga Wash near Los Angeles, California, captured the river, the knickpoint migrated upstream to undermine nearby highway bridges (Scott, 1973).

The negative effects caused by breaching a small (5 acres or less) or shallow (10 ft) flood-plain pit may be negligible and may add channel complexity to a channelized river. If the pit is small and shallow relative to the river, it may quickly fill with sediment. However, even small gravel pit lakes in locations that are prone to avulsion or near structures can be problematic. For example, in Clark County near Vancouver where Salmon Creek crosses I-5, an avulsion in 1996 into small (<5 acres) gravel pits caused 4 ft of knickpoint incision at a county bridge 1/4 mi upstream and has created a fish passage barrier for steelhead, a threatened species on Salmon Creek (Ken Bates, WADFW, oral commun., 1998).

After avulsion has occurred, the temporary fluvial base level is the pit bottom. Therefore, for a considerable distance upstream, the river channel tends to incise and straighten as it works to establish a new equilibrium and grade. Because of this, existing channels (and salmon habitat) may be abandoned and replaced by a deep channel as wide as the pit. Sediment eventually fills the pit, and a new stream channel is formed. While the breached pit is gradually filling with gravel from upstream sources, little gravel will be transported past the pit to downstream areas. The downstream channel and bars

consequently will erode if they are not replenished with coarse bed material. The river, in essence, mines its own gravel bars, becomes less stable, and is inhospitable to salmon.

The time required for the river to re-establish equilibrium depends on the size and depth of the pit, the river’s ability to transport sediment, and the availability of sediment (Woodward-Clyde Consultants, 1980a,b). It can also depend on the instabilities caused by the headcut upstream or bedload depletions downstream. If the river has already eroded down to bedrock in its upper reaches and sediment is not available, equilibrium may not be re-established for a very long time.

**EXAMPLES OF FLOOD-PLAIN SAND AND GRAVEL MINING AND STREAM CAPTURE**

Recent avulsion and stream capture events at gravel mines in Washington are listed in Table 1. The following paragraphs discuss some of these events.

**Cowlitz River Upstream of Toledo**

In November 1995 after heavy rains, the Kirkendoll revetment at river mile 38 on the Cowlitz River failed (Fig. 10). About a quarter of the Cowlitz flow rushed through the opening and across the IFA Nursery, then found its way to a gravel pit near the river 3,200 ft downstream between river miles 36 and 37. The mine pit partially filled with sediment and debris in a matter of days. Part of the river severed access to about 13 homes until residents were able to construct a temporary dike of loose sand and gravel across the breached area as waters receded. During the February 1996 (Fig. 11) event, the Cowlitz River breached this temporary dike and re-established itself in the 1995 channel. During the November 1995 event, the Cowlitz River flow was greater than 68,400 ft$^3$/sec as measured below Mayfield dam, approximately 18 mi upstream. (This value is the maximum flow that can be recorded on that instrument, and no estimate was made as to amount of flow above that value.) During February 1996, the flow at the Mayfield dam was not as high, but tributaries downstream of the dam were contributing more water than they had in November 1995 (Stephanie Zurenko, Washington Department of Natural Resources [WADNR], oral commun., 1997).

Because the pits behind the Kirkendoll revetment were only 20 acres in area and less than 20 ft deep, no obvious changes to the grade of the river occurred. During flooding and filling of the pit, scouring deepened the new channel and a knickpoint migrated upstream, as evidenced by a moving wave immediately upstream of the pit and at the revetment (Stephanie Zurenko, WADNR, oral commun., 1997). However, no agencies did a survey of the elevation of the river bed before and after the avulsion to determine if the event had caused incision.

When the February 1996 flood receded, water was diverted back into the pre-November 1995 channel by repairing the dike. The scouring and downcutting between the IFA Nursery and the gravel pit were then evident. According to the U.S. Army Corps of Engineers, complete abandonment of the 1995 channel would likely have occurred if the revetment had not been replaced and reinforced with riprap in the summer of 1996 because the existing Cowlitz River bed was higher than the area protected by the revetment (Stephanie Zurenko, WADNR, oral commun., 1997). Most of the material deposited in the pit consisted of fine sediment. The large amount of sand, silt, and soil present was probably derived from the nursery. Stumps and logs were also deposited in the pit. Because of the debris, miners now use an excavator rather than the former dragline to excavate gravels. The large volume of sand, soil, and debris in the pit likely makes this gravel mine less valuable.

**Figure 9.** A. A profile of a streambed before mining. B. The same profile showing a depression excavated in the stream bed when stream flow is not strong enough to move the bedload. The knickpoint is where the stream profile abruptly changes. C. During high flows, or once avulsion and breaching begin, the knickpoint immediately retreats upstream as the sediment at that location is removed by erosion and deposited in the pit or downstream and the river tries to re-establish its grade and equilibrium. The high flow also attacks the downstream side of the depression where the slope also changes. (Modified from Kondolf, 1993.)

**Table 1. Recent avulsions or stream captures**

<table>
<thead>
<tr>
<th>Location or operation</th>
<th>River</th>
<th>Year</th>
<th>Location</th>
<th>Date mined</th>
<th>Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Ridgefield pits</td>
<td>East Fork Lewis</td>
<td>1995</td>
<td>sec. 19, T4N, R2E</td>
<td>1960s</td>
<td>6</td>
</tr>
<tr>
<td>Ridgefield pits</td>
<td>East Fork Lewis</td>
<td>1996</td>
<td>secs. 13, 24, T4N, R2E</td>
<td>1980s-90</td>
<td>70</td>
</tr>
<tr>
<td>Salmon Creek Park ponds</td>
<td>Salmon Creek</td>
<td>1996</td>
<td>sec. 35, T3N, R1E</td>
<td>early 1970s</td>
<td>5</td>
</tr>
<tr>
<td>Pits upstream of Toledo</td>
<td>Cowlitz</td>
<td>1995, 1996</td>
<td>sec. 10, T11N, R1W</td>
<td>ongoing</td>
<td>20</td>
</tr>
<tr>
<td>Gravel pits at Toledo</td>
<td>Cowlitz</td>
<td>1995, 1996</td>
<td>secs. 8, 17, T11N, R1W</td>
<td>ongoing</td>
<td>108</td>
</tr>
<tr>
<td>Mouth of Wynoochee River</td>
<td>Wynoochee</td>
<td>1984</td>
<td>sec. 18, T17N, R7W</td>
<td>1960s</td>
<td>20</td>
</tr>
<tr>
<td>Walker pit</td>
<td>Yakima</td>
<td>1996</td>
<td>sec. 36, T11N, R20E</td>
<td>1960s</td>
<td>12</td>
</tr>
<tr>
<td>Parker pit</td>
<td>Yakima</td>
<td>1996</td>
<td>sec. 20, T12N, R19E</td>
<td>1980s</td>
<td>35</td>
</tr>
<tr>
<td>Selah Gap pits</td>
<td>Yakima</td>
<td>1996</td>
<td>sec. 31, T14N, R19E</td>
<td>ongoing</td>
<td>250</td>
</tr>
<tr>
<td>Gladmar Park</td>
<td>Yakima</td>
<td>1996</td>
<td>sec. 13, T18N, R17E</td>
<td>1960s</td>
<td>30</td>
</tr>
<tr>
<td>I-90 pits</td>
<td>Yakima</td>
<td>1996</td>
<td>sec. 29, T18N, R18E</td>
<td>1960s</td>
<td>20</td>
</tr>
</tbody>
</table>

**Figure 9.** A. A profile of a streambed before mining. B. The same profile showing a depression excavated in the stream bed when stream flow is not strong enough to move the bedload. The knickpoint is where the stream profile abruptly changes. C. During high flows, or once avulsion and breaching begin, the knickpoint immediately retreats upstream as the sediment at that location is removed by erosion and deposited in the pit or downstream and the river tries to re-establish its grade and equilibrium. The high flow also attacks the downstream side of the depression where the slope also changes. (Modified from Kondolf, 1993.)

**Cowlitz River at Toledo**

Extensive gravel mining occurs along the Cowlitz River at Toledo (Fig. 12). Before the mid-1930s, the course of the Cowlitz River near the gravel pits between river miles 34 and 35 consisted of two or more channels (Collins,
Figure 10. Vertical air photo (July 1996) of the Cowlitz River from Toledo to approximately 3 mi upriver. Flow is to the left. Arrows show the scoured paths of the November 1995 and February 1996 floods. The Kirkendoll revetment was designed by the U.S. Army Corps of Engineers to contain a flow of 48,000 ft³/sec. Homes labeled are those isolated by the 1995/1996 floods. The river broke through the revetment into the 1854 channel because it was higher than the adjacent flood plain downstream of the revetment. The gravel pit had filled with sediment during the November 1995 flood, so there was no significant deposition there from the February 1996 flood. Peak flow during the November 1995 flood may have exceeded the 68,400 ft³/sec measured at the Mayfield Dam station 13 mi upstream of Toledo, but the February 1996 peak flow was less than 44,900 ft³/sec at the dam (Luis Fuste, USGS, oral commun., 1998), where average winter flows are approximately 20,000 ft³/sec. The USGS calculates the 100-year event flow to be 91,448 ft³/sec (Williams, 1985). The pits at Toledo are predominantly in the 1937 and 1854 channels. Note that prior to 1937, the Cowlitz River had more than one channel at the Toledo gravel pits (Collins, 1996). After 1937, the Cowlitz was channelized. Arrows indicate the locations of the November Toledo dike failure and partial capture of the Cowlitz. Dike failure continued until water receded after the February 1996 event. There is no longer a gaging station at Toledo, so there is no information about flood flow at the pit. The dike at the upper end of the gravel pit lake was rebuilt by the mining company. The pit is still connected to the river at the lower end to allow fish access.
The Cowlitz River, as mapped in 1854 and even in 1941, had a much more complicated course and flood plain than it does today (Fig. 10) (Collins, 1996). The river is now channelized and pinned between the gravel pit lakes and the bluffs on which the town of Toledo has been built. Mining occurs in the 1937 and 1854 channels, the side channels, sloughs, marshes, and oxbows along the river.

During the November 1995 and February 1996 floods, the gravel pits, including stockpiles, and processing areas were inundated (Fig. 13). The dike (constructed of sand and gravel) protecting the gravel pits from the river failed and allowed some of the water to flow into one of the ponds close to the river. The river breached a riparian buffer area as it exited the lower pond. After the flood, sand and gravel was bulldozed by the mine operator to form a new dike in the area of the upper breach, forcing the river into its former channel. The lower breach was left open to allow fish access to the ponds, which are no longer mined. The remainder of the site is being mined. As at the pits upstream of Toledo, the effects of the avulsion at Toledo on the bed of the Cowlitz River were not measured, and the total volume of material moved was not estimated.

Yakima River at Parker

During the February 1996 flood, part of the Yakima River avulsed through the gravel pits near Parker between river miles 105 and 106 on the south side of Union Gap (Fig. 14A,B). Ice jams may have played a role in stream diversions in this instance. The river entered several gravel pit ponds totaling 35 acres and averaging 10 ft deep. Mining stopped at this depth because a 100-ft thick clay layer underlies the gravel in this reach (Len Sali, Columbia Redi-Mix, oral commun., 1998). Because the surfaces of the gravel pit lakes were lower than the river level and the low-flow course of the river was around the pit.
gravel pits, it was inevitable that the river would avulse at flood stage.

The flood breached the dikes in two places at the north end of the ponds. The miner attempted to fill the breaches with rip rap; however, the Washington Department of Fish and Wildlife stopped the operation before filling was complete because the miner had no permits. One breach was partially filled, and the other remains as it was after it was breached during the flood. The dike openings where the channel flows into the ponds are approximately 100 ft in width. On their upstream ends, the pits have begun filling with gravel and are now about 4 ft deep. At the lower end of the mine, the river exits through two outlets that are about 50 ft wide (Len Sali, Columbia Redi-Mix, oral commun., 1998).

The river currently has a braided, meandering course through the ponds. In this instance, the channel has become more complicated, and because the ponds were shallow, no negative effects have been recorded by regulatory agencies. However, there is no monitoring of the site. No further extraction will occur at the site, but crushing and asphalt batching of material brought to the site is ongoing.

**Yakima River at Selah Gap**

During the flood of February 1996 at Selah Gap, ice jams, high water flow, and gravel mining combined to cause avulsion into Washington’s largest (areally) flood-plain mining area. The mined area covered approximately 250 acres, and the maximum depth of excavation was about 25 ft (Fig. 15). When the dike upstream of the pit was breached, the entire Yakima River flow entered the gravel pits between river miles 118 and 120, exiting at the downstream end of the site (Fig. 16).

During this flood, the peak flow of the Yakima River was 27,200 ft$^3$/sec as measured at the Umtanum gaging station 18 mi upstream and above Roza dam. The calculated 100-year event at Umtanum station is 27,459 ft$^3$/sec (Williams and Pearson, 1985b). Large ice jams played an undefined but likely significant role in the avulsion. Approximately 8,000 ft of channel was abandoned when the flood waters receded.

Results of the avulsion are difficult to quantify. About 6 to 8 ft of incision occurred immediately upstream. There was local knickpoint migration as evidenced by a migrating standing wave and increased bank erosion as the river began to re-establish its grade (Lorraine Powell, WADNR, oral commun., 1996). We estimate that at least 300,000 yd$^3$ of gravel was scoured from the river bed and deposited as a layer a minimum of 6 ft thick in the excavated pits over a 33-acre area. We also estimate that more than 100,000 yd$^3$ of gravel was moved from the river bed during the flood and deposited on gravel bars and private lands just upstream of the pits.

Dike building (Fig. 17) forced the Yakima River back into its pre-February 1996 channel by September 1996. As a result, river bed disruption and incision were halted or slowed. However, because of concerns about such floods in the future, the mining company decided to rebuild the dikes that tightly constrain the river. These dikes increase the erosive power of the river further downstream. The mine operator also installed an engineered armored spillway at a low point in the dike that allows the river to overtop it there and reduce its flow. This sill keeps the bedload in the main channel and reduces the potential for incision in this area.

**East Fork Lewis River near La Center**

On the East Fork Lewis River, in Clark County, intensive mining has occurred between river miles 8 and 9. The river has not
been dammed and has one of western Washington’s few remaining wild (native) steelhead runs. This fish has been listed as threatened on this river. Gravel mine ponds on both sides of the river cover approximately 200 acres, average about 30 ft deep, and are sited in abandoned channels in this formerly braided river system (Fig. 18) where the river issued from a V-shaped valley onto a broad complex flood plain. The

Figure 15. The Yakima River and gravel pits near Selah Gap in 1994. During the flood of February 1996, breaching of the dike caused the entire flow to enter the gravel pits between river miles 118 and 120 and eventually exit at the downstream end. After the flood, diking and other river training devices built by the mining company diverted the river back into its original channel.

Figure 16. Selah Gap pits between Interstate Highway 82 and the Yakima River. Most of the gravel pit lakes are located in the 1866 and 1936 channels. Traces of numerous meander scars and oxbow cutoffs from earlier, natural lateral channel migrations remain, west of the river. Note the path of the February 1996 avulsion. In this September 1996 photo, dikes have returned the Yakima River to its February 1996 channel.
current pits occupy approximately two-thirds of the mile-wide valley and most of the 100-year flood plain in this reach. Several dike failures, avulsion events, and diversions have occurred along the river.

During November 1995, the river avulsed through a gravel pit pond at mile 9 (sec. 19) and abandoned about 1,700 ft of channel (Fig. 19) and spawning gravels. During February 1996, the east fork flooded again. The Heissen gaging station...
located approximately 10 mi upstream of the gravel pits was washed out in this flood, but the peak flow was indirectly estimated at 28,600 ft³/sec by a U.S. Geological Survey (USGS) hydrologist. Earlier calculations (Williams and Pearson, 1985a) indicated the 100-year peak flow event at Heissen to be 20,046 ft³/sec. Since the 1996 flood event, the 100-year event has been recalculated by the USGS at 22,200 ft³/sec, using the 28,600 ft³/sec observation as the maximum peak flow (Sumioka and others, 1998). No avulsion of the east fork into the lower gravel pits occurred during this event. However, significant bank erosion set the stage for eventual stream capture.

In November of 1996, the river avulsed through six closely spaced gravel pit ponds on the south side of the river and the river eventually abandoned about 3,200 ft of channel and spawning gravels. Avulsion began near an outside bend of the river near the haul road from the pits (Fig. 20). Lateral channel migration and the series of floods severely eroded the road, which had acted as the dike to keep the river out of the pits. The main stem was captured and now flows through the south bank gravel pits (Fig. 21).

Some of the results of the avulsions are:
- about 10 ft of channel downcutting as the knickpoint migrated upstream,
- increased erosion along the south bank,
- abandonment of about 4,900 ft of channel where salmon and steelhead had spawned, and
- sluggish flow through the gravel pits.

The depth of downcutting was estimated as the height difference between the bed of the abandoned channel and bed of the current channel. The severity of the effects may be related to the fact that these ponds were much deeper and wider than the normal river channel. We estimate that it will require more than 2 million yd³ of sand and gravel, which must be derived from the channel and banks, to refill the 70-acre pits through which the river flows.

**STATE MINING REGULATIONS**

The principle law regulating activity on the shorelines of the state is the Shoreline Management Act (RCW 90.58), which is administered by cities and counties. Many local jurisdictions also regulate floodplain mining under provisions of conditional use permits or other land-use ordinances and the Growth Management Act (RCW 36.70A). Several counties also have mining ordinances. The Shoreline Management Act generally applies to mining activities on the 100-year floodplain and associated wetlands. Regulation may vary according to the “master plan” of each local jurisdiction. For instance, in Lewis County, the Shoreline Management Act applies only to areas within 200 ft of the floodway of flooding that occurs with reasonable regularity, although not necessarily annually, or the ordinary high water mark if the floodway is not mapped. When mines are proposed, the local jurisdiction becomes the Lead Agency under provisions of the State Environmental Policy Act (SEPA). The Washington Department of Ecology (Ecology) must also give its approval to terms of a Shoreline or Conditional Use Permit issued by a local jurisdiction. Ecology’s 1994 Shoreline Management Guidebook recommends that local governments encourage miners “to locate activities outside the shoreline jurisdiction” — in other words, generally 200 ft from the floodway, or off the 100-year floodplain.

Several other agencies of secondary importance have responsibility for regulating mining on floodplains and rivers. Any work, including mining, that uses, diverts, obstructs, or changes natural flow or the bed of any waters of the state requires a Hydraulic Project Approval (RCW 75.20-100) from the Washington Department of Fish and Wildlife (WADFW). However, because WADFW jurisdiction is restricted to waters of the state, the agency may not have jurisdiction over floodplain mining if mining does not involve the active channel. After an avulsion has occurred WADFW would have jurisdiction over any work occurring in the pits/river. The Department of Natural Resources administers the Surface Mine Reclamation Act (RCW 78.44), which generally requires mines to be reclaimed immediately after each segment is mined. The 1993 revision of this law requires that most mines in floodplain environments be reclaimed as beneficial wetlands. As part of the reclamation plan for a mine, the act also requires that “where mining on flood plains or in river or stream channels is contemplated, a thoroughly documented hydrologic evaluation that will outline measures that would protect against or would mitigate avulsion and erosion as determined by the department” be included.

The U.S. Army Corps of Engineers regulates excavation or filling of wetlands through section 404 of the Clean Water Act.
Most flood-plain mines would occur in wetlands or portions of wetlands and would be required to apply for a section 404 permit.

The Growth Management Act (RCW 36.70A) directs counties to designate “mineral resource areas” and “critical areas” such as wetlands or “fish and wildlife conservation areas” that include water of the state (Lingley and Jazdzewski, 1994). However, the Growth Management Act has not been fully implemented and does not apply to all counties.

As wild salmon populations dwindle and the fish are listed as threatened and endangered species, the Endangered Species Act may play a role in future siting of riverine mining. It is not yet clear what that role will be.

A complete discussion of regulations for mining is given in Norman (1994).

Recommendations for Planning and Siting

Mine site selection or plans for mine expansion should not be made on the basis of a perception that, because gravel mining has occurred historically in an area, it is appropriate to continue mining or that river rock is the only source of construction aggregate in that market. Potential consequences of mining can be severe, and the function of the flood plain can be lost, along with fish and wildlife habitat. Wherever possible, large gravel mines should be located in uplands away from the river.

Figure 20. A. Before avulsion of the East Fork Lewis River. In the center of this 1990 photo are the bank and haul road that were breached in 1996. The river is at the top right. A gravel pit lake is at the lower left. A pole and portable screen are at the left. B. After avulsion, the haul road/dike has been breached, and the river flows into gravel pits. The remains of the haul road can be seen on the left across the river. “A” indicates same spot on each photo. The abandoned channel of the river is shown in the center right of photo. Approximately 10 ft of incision has occurred immediately upstream of where the river entered the pits. Taken February 1998 from approximately the same position as A. C. This February 1998 view shows the present position of the East Fork Lewis River; the drift boat is entering the former pit area. At the top right is the remnant of the old haul road. The gravels and cobbles in the foreground are the old river bed after avulsion. About 10 ft of incision has occurred here, on the basis of the difference between the height of the abandoned channel thalweg and the present-day channel.
valley floors. A poor second choice is to locate mining on terraces and the inactive flood plain, that is, above the 100-year flood plain. In Washington, upland deposits offer ample rock supplies. Mining these deposits eliminates potential for stream capture or river avulsion. Furthermore, pits in these locations have a good potential for successful long-term reclamation.

In parts of Europe and the eastern United States, gravel is slowly being replaced by crushed quarry rock for use as construction aggregate. In these areas, the transition is occurring mainly because limited gravel resources are nearly depleted. However, substitution of crushed quarry rock for gravel has distinct environmental advantages in that considerably more rock is produced from quarries for the surface disturbance and quarries can easily be located away from flood plains and aquifers. The relatively small disturbance occurs because most quarries contain 100 percent usable rock, whereas gravel deposits have high porosity (meaning less material per volume) and fines that are not economic.

If mine plans call for sites on flood plains, then wide, topographically higher, and thickly vegetated buffers should be considered as a means of reducing the probability of river avulsion in the near term. In some places, buffers may be effective because the river may not utilize the entire flood plain. However, in most instances, buffers only delay the inevitable. Determining an adequate distance between the flood-plain mine-pit lake and the river will depend on understanding the rate of river meandering and the risk of avulsion.

If flood-plain mining is approved, the main goals of planning, siting, and reclamation are:
- The mining should not increase the potential for river avulsion.
- Fish and wildlife habitat should be protected.
- Riparian areas should be protected, both to provide habitat and to improve flood-plain stability.
- Reclamation should ultimately enhance salmon habitat (Norman, this issue, p. 21).
- If there is potential for migration of the river into a gravel pit, the site must be reclaimed in a way that is hydrologically compatible with the adjacent river.

Figure 21. Vertical air photo of the East Fork Lewis River showing the course of the river in November 1997. At A, the river changed its course into a gravel pit in 1995. The river re-entered its channel at B. The channel between A and B is now abandoned. C indicates where the haul road was breached and the river avulsed into the gravel pits in 1996. D marks the start of the channel abandoned in this event. E is along the avulsion path as the river finds its way through the series of ponds. The river re-enters its old channel at F. The valley walls are approximately 1 mi apart near the gravel pits.
Environmental Analysis

Before any new mining or expansion is allowed on a flood plain, miners must make a rigorous environmental analysis of the mining plan. This should include, at minimum, a geohydrological analysis of the affected reaches of the river system. A thorough plan will also include:

- a topographic map of the existing conditions and surrounding lands at a 2-ft contour interval and at an appropriate scale, as well as flood profiles;
- maps and cross sections that show depths and locations of all bodies of water, the stream profile, and the elevation of the river bed measured from a permanent station, such as a nearby bridge, near the gravel mine;
- a geomorphic analysis that identifies historic channels and channel migration trends on the basis of examination of all available data, such as historic air photos and maps, and that considers geological and artificial controls of the channel, such as armored banks, dikes, bridges, dams, and other mine sites;
- a detailed chronology and description of historical precipitation, flooding, discharge, sediment transport, including description of sediment sizes in and adjacent to the proposed mine site;
- maps of vegetation and analysis of its role in flood and erosion control, as well as a description of the relation between the sediment distribution and the biota, especially as it applies to bank erosion and avulsion;
- an analysis of avulsion or stream capture potential, including the consequences of stream capture, channel incision, and scouring;
- an analysis of potential damage to neighboring properties, fish and wildlife habitat, bridges, and rights-of-way and the effects of existing or proposed dikes and levees and their long-term maintenance;
- an analysis of channel stability, magnitude and frequency of the 5-, 10-, 25-, and 100-year floods, channel and flood-plain hydraulics near the proposed mine site, and any previous stream capture events; flow paths for the 5-, 10-, 25-, and 100-year floods before and after the mining project;
- a carefully documented study of potential impacts to salmon species listed under the Endangered Species Act.

In summary, because flood-plain gravel pits are in the dynamic riverine environment, the environmental analysis should be undertaken with great care, taking into account long-term stability of the site, and include proposals for enhancing or restoring the site’s fish and wildlife habitat.

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Reclamation of Flood-Plain Sand and Gravel Pits as Off-Channel Salmon Habitat

David K. Norman
Washington Department of Natural Resources
Division of Geology and Earth Resources
PO Box 47007, Olympia, WA 98504-7007
e-mail: dave.norman@wadnr.gov

INTRODUCTION

Many permitted sand and gravel mining sites located on Washington’s 100-year flood plains will require reclamation. However, even in the long term, reclamation may not restore the entire ecologic function of the flood plain (Collins, 1996, 1997; Kondolf, 1993). Nonetheless, opportunities exist in some places to develop highly productive wetlands and off-channel habitat for salmon, many species of which are struggling to maintain strong populations.

Side-channels and oxbow lakes connected to the main stem of a river are types of wallbase channels or off-channel sites that are primary overwintering habitats for juvenile coho salmon and cutthroat trout (Cederholm and Scarlett, 1981, 1991; Peterson and Reid, 1984). Enhancing areas of reclaimed habitat is most feasible in small (<5 acres), shallow gravel pit lakes (Fig. 1) where wallbase channels can be mimicked. Large, deep gravel pit lakes may not be convertible to off-channel habitat. Furthermore, the consequences to the riverine environment of either avulsion or maintaining isolation from the river with dikes are much greater at deep pits (Norman and others, this issue, p. 3) than at a small pit, which may be left unprotected.

Wallbase channels are created on flood plains where runoff is channeled through swales created by the migration of the main stem river. These channels can develop either along abandoned meanders or between the long ridges (termed scroll bars) in a large meander loop that are built at the inner edge of the low-water channel during bankfull stages. In most places, wallbase channels appear as swamps, ponds, or small tributaries and are connected to the main stem of the river. In spring and fall, juvenile salmon move out of the main river and into tributaries and side channels to spend the following season (Cederholm and Scarlett, 1981; Peterson and Reid, 1984). Off-channel habitats also provide refuge for overwintering coho (Brown, 1985), chinook, and steelhead, and chum salmon spawn in these areas (Fig. 2) (Grays Harbor College and others, 1990). Efforts to enhance some natural wallbase channels and overwintering ponds as environments for juvenile coho salmon have met with success (Cederholm and others, 1988; Cederholm and Scarlett, 1991; Peterson, 1985).

The success of projects that convert gravel pit ponds to off-channel habitat generally depends on the following factors:

- good access for fish to leave and enter main river channels,
- low risk of avulsion (stream capture), flooding, or drought, and
- adequate cover, food supply, and water quality (Samuelson and others, 1997).

Fairly shallow, small ponds that have complex shapes and are in areas that are not frequently flooded or likely to be affected by avulsion are the best candidates for this type of reclamation. Only the edges of large, deep gravel pit lakes are productive habitat for salmon; the lack of cover and aquatic plants elsewhere in the water is not attractive to these fish (Norman and others, this issue, p. 3).

Carefully prepared site plans and well-executed reclamation can enhance site stability so as to maximize the longevity of the new habitat without the use of dikes. When preparing mine plans, miners should consider the location, size, shape, and depth of pits, as well as local geomorphology and hydrology, in order to preserve flood-plain and river dynamics during and after mining. Revegetation of the reclaimed riparian zone should concentrate on establishing dense growths of diverse...
vegetation. These plants will create a zone of soils bound by roots that will slow erosion and reduce floodwater velocities.

To begin rehabilitating the function of the riparian zone and associated wetlands, revegetation plans should take into account the potential for attracting a wide variety of aquatic and terrestrial wildlife, including amphibians and reptiles. Aquatic vegetation as cover and environments that promote insect populations for food will benefit the salmon. Approaches to creating or restoring wetlands in gravel pits are reviewed by Norman and Lingley (1992), Michalski and others (1987), Prange (1992), Norman and others (1996), and Stevens and Vanbianchi (1993).

This paper focuses on principles and techniques to be considered in establishing salmon habitat in reclaimed gravel pit lakes and describes some successful examples.

DESIGN OF RECLAIMED PONDS FOR OFF-CHANNEL SALMON HABITAT

Benefits

Gravel pit lakes can be reclaimed to imitate natural oxbows and cutoff channels, commonly already present on a flood plain, that are connected to the main channel (Collins, 1997; Norman and others, this issue, p. 3). Off-channel habitat offers numerous benefits to salmon. Juvenile salmon will migrate into wallbase channels to seek shelter from strong currents and turbid water during freshets in April and May and the first freshets in the fall. Young salmon typically feed in the shallows and hide in water deeper than 6 ft or in complexes of woody debris in these channels. A few modifications, such as adding woody debris or aquatic plants, to a reclaimed pond design will greatly increase the ponds’ utility for salmon. This created habitat would be similar to natural wallbase channels.

While in these channels, salmon take advantage of the rich food supply of aquatic insects, for example, chironomid larvae, that live on the abundant aquatic and riparian vegetation and in the slow currents. They also eat copepods (small crustaceans) and oligochaetes (such as earthworms) that live on or in the pond floor. Because these juvenile salmon migrants have grown larger in these channels than their contemporaries in other environments, their chances of survival are improved.

Pond Shapes and Depths

Gravel pit lakes with a regular shape (chiefly rectangular), steep slopes (1.5 horizontal:1 vertical), and uniform depth offer little habitat complexity for fish and wildlife (Kondolf, 1993). A productive gravel pit lake connected to the main stem river can result if the mine operator constructs or reshapes ponds so that they have irregular shorelines and a variety of depths (Fig. 3).

An arrangement of gravel pits that benefits salmon is a series of connected irregular ponds that have islands and peninsulas (Fig. 4). The shoreline length is maximized, and the connections between ponds provide channels with riffles, thus increasing the dissolved oxygen content and adding complexity.

Gradually sloped, complex reclaimed shoreline margins help promote aquatic plant development. If the bottom of the pond is irregular, it will offer a range of habitats for plants, benthic fauna, and fish.

Optimal slopes in shallows intended as fish habitat are flattened to at least 5H:1. Slopes of 15H:1V (3 ft water depth at 45 ft off shore) would provide a broad rim with the potential for diverse aquatic plant growth. Where a shoreline slopes steeply, marsh conditions and space for aquatic plants are confined to a narrow band (Andrews and Kinsman, 1990).

Maintaining approximately 25 percent of the lake as benches and bars less than 2 ft deep, 25 percent as areas 2 to 6 ft deep, and half the lake more than 10 ft deep provides the complexity that enhances biotic diversity (Norman and Lingley, 1992; Norman and others, 1996). For fish and wildlife habitat, the higher the percentage of shallow areas, the better the potential for both food production and shelter in aquatic plants and woody debris that has fallen in the pond.

Some of the shallow gravel shelves along a pit lake perimeter will be places where ground-water flow is intercepted. Upwelling generally occurs along the hydrologic upgradient of ponds. This water is typically well oxygenated, and chum salmon are known to choose these ground-water-fed shallows (<2 ft deep) for spawning (Grays Harbor College Research, 1990).

Wallbase channel gravel pits should be designed to minimize chances or consequences of avulsion. This can be achieved by keeping wallbase channel ponds shallow, small (<5 acre), longer than wide, parallel to the river, and away from

![Figure 3. The shorelines of ponds used for wildlife habitat should be irregular and planted for cover with a mixture of open meadows and shrubs in the surrounding area. The shape of the pond on the left is better suited to supporting wildlife than that of the pond on the right. (Modified from Szafoni, 1982.)](image)
actively meandering channels (Fig. 4). Habitat ponds must be connected with the river on the downstream side (Norman and others, 1996) for optimal fish access. A channel connected on the upstream end can offer a route for river avulsion.

**Substrates**

Off-channel habitat should be designed for a variety of uses by preserving gravel substrates that could be used as spawning areas and by placing soil to accommodate aquatic plant growth. Topsoil in shallow water facilitates revegetation and speeds re-establishment of a food chain. Soils placed in the shallows provide a mud bottom that is generally a nutrient-rich substrate for bacteria, plants, and benthic macroinvertebrates. If these food sources and sheltered areas are plentiful, young salmon have a better chance of reaching maturity.

Choice spawning substrates generally have a combination of round gravels ranging from 0.25 to 3 in. in diameter and moving water. Suitable spawning areas may also be provided by (a) springs welling from the pond bottom or sides where the ground-water table has been intercepted by the excavation or (b) those parts of the channels connecting ponds where water is moving across gravels. In addition, coarse gravels and cobbles are home to preferred salmon food sources such as immature stages of caddis flies and mayflies. Juvenile fish also hide in coarse gravel. Most of the pit lake floors and channel banks should be covered with soil, which will be the most productive substrate for vegetation and insects.

Miners are required by Washington law (RCW 78.44) to save and replace all topsoil and sediments within 4 ft of the surface and to practice segmental reclamation. Topsoil should be directly replaced from one area of a mine to another without a period of storage. Wherever possible, 12 to 18 in. of the “A horizon” topsoil should be placed on banks and islands and in all shallow areas of the new pond to the depth that light penetrates through the water.

**Aquatic Vegetation**

A network of aquatic plants shelters fish from predators. The soil placed on the lake shore or in shallow water promotes growth of sedges, reeds, lily pads, and other aquatic vegetation. Plants also are essential to insect populations. The surface area of plants may be many times greater than that of the pond or lake bed; hence plants may considerably increase the amount of surface area that insects can colonize. Many insect species lay their eggs on plants. Dead and decaying plants are also a food resource for insects (Andrews and Kinsman, 1990).

Juvenile coho salmon feed on insects of the family Chironomidae (non-biting midges) as the young insects emerge through the shallow water column (Peterson, 1982a,b). Chironomids are found in a variety of freshwater substrates. However, population densities in sand are generally very low, and gravel and rock usually support high densities only where well covered with algae. By contrast, organic sediment and plant surfaces can support high chironomid population densities.

Aquatic plants can help slow or prevent erosion on a shoreline that is subject to wave erosion by absorbing moderate wave energy. Exotic plant varieties rarely provide the same benefits as natives. Aggressive native species, such as common cattail and Douglas’ spiraea, should be used cautiously or avoided completely because they tend to become a virtual monoculture.

If there are wetland areas within the site before gravel pit excavation starts, then the aquatic plants and muck soil layer should be carefully protected and moved into the pond during the reclamation process. Many aquatic plants grow and propagate themselves vigorously. The initial introduction need not be vast, and early-planted material may be thinned for planting during later reclamation stages. Planting times will vary, depending on the requirements for successful establishment of each species.

**Upland Vegetation**

Planting riparian areas with native tree species (for example, cottonwood, poplar, alder, willow, fir, spruce, cedar, pine, maple) and native grasses, sedges, legumes, and forbs can accelerate the process of providing productive habitat, create diversity, and help stabilize the site. Deciduous trees and shrubs, especially willow and alder, are valuable sources of food for insects because their submerged, fallen leaves rapidly degrade and develop a microfauna of bacteria, fungi, and protozoa (Andrews and Kinsman, 1990).

Native plants should always be used for this kind of revegetation, preferably those species that grow close to the site. Planting willow, osier dogwood, poplar, and cottonwood cuttings is an effective and fairly quick method of building a root matrix that can slow erosion. Planting should take place in the spring or fall, preferably while plants are in the dormant stage (Norman and others, 1996).

**Buffers**

To reclaim a mine site as off-channel habitat, miners should plan and maintain areas of undisturbed riparian vegetation as setbacks from rivers. Wide buffers delay a river’s entry into a pit by giving the river room to migrate and to disperse floods. Buffers of well-rooted vegetation on banks and in the riparian zone slow erosion and will extend the time that the gravel pit off-channel habitat exists. Highly vegetated buffers can be seed sources of plants, which will speed the revegetation process.

Figure 4. Plan view and cross section of a reclaimed gravel pit with a pond shape that mimics a natural river system. Not to scale. (Modified from Woodward-Clyde, 1980.)
Calculating an appropriate buffer width may be difficult. In general, the width selected should be based on stream and valley morphology and the rate at which the river migrates. Buffer widths should be adequate to protect or restore full function to both the river and the pits. The Washington Department of Fish and Wildlife (WADFW) recommends that the riparian habitat area be at least as wide as the 100-year floodplain or 250 ft, whichever is greater (Knutson and Naef, 1997).

When designing buffer revegetation, miners should consider the orientation of the area relative to the sun. For instance, a north-facing slope receives less sun than a south-facing slope and is likely to be easier to revegetate because it dries more slowly and remains cooler.

Livestock should be excluded from the reclaimed ponds and riparian areas because they can trample and overgraze vegetation and adversely change the water quality.

**Coarse Woody Debris and Shelter**

Overwintering success for juvenile salmon in off-channel areas can be greatly enhanced by adding large woody debris, which provides cover. Side channels that contain such debris had more coho than channels with no woody debris (Sedell and others, 1984; Tschaplinski and Hartman, 1983). Trees need not completely surround a floodplain pond or completely line a channel, but the more enclosed the reclaimed lake, the better the habitat. Eventually, large woody vegetation along the shoreline will fall into the pond and provide further habitat for fish. If none is present, woody debris should be placed on the shore and at a variety of depths.

Logs and stumps can be lashed together to form debris jams in the wallbase gravel pits ponds. They may be anchored by rocks, overburden, or soils. In water 20 ft deep, logs and stumps form reef habitat (Fig. 5) for fish and aquatic insects. Stumps with their intricate masses of rootlets still attached (root wads) provide cover and can be easily and cheaply added to ponds. Large boulders can also be used to build reefs (Norman and Lingley, 1992; Norman and others, 1996).

Submerged and anchored tree crowns provide excellent cover along steep banks (Norman and others, 1996). Trees most suitable for aquatic habitat restoration of this kind are cedar and fir. Alder can be used if no other trees are available; however, deciduous trees generally decompose too quickly.

**Connection to the River**

If the reclaimed floodplain mine is near the active river channel, not deeper than the deepest part of the adjacent river, not subject to drying up, and not susceptible to flooding, ponds can be connected to the river at the downstream end. These outlet connections (ingress/egress channels) allow fish to enter and leave the off-channel ponds. Where feasible, connections to a river should be made by way of natural wallbase channels or sloughs that enter the main river and flow near the ponds. Other natural features that mimic the natural riverine system, such as side channels along gravel bars, can be effective connections if the bar is stable. Connections to rivers should not be straight or constructed where a stream is depositing sediment.

For fish, the ideal entrance to a pond is located adjacent to a main stem channel irregularity that creates a large to moderate eddy; fish can recognize the plume of clear water flowing from the pond into the main river. Connection gradients should be gentle (0–1%). Logs can be laid in the connection channel to provide "steps" to lower the gradient and create pools in which fish can rest.

Riffles or fast water areas are less desirable outlet sites because fish do not spend much time there and may not find the outlet. Very shallow outlets may be left high and dry during low water. The designed ingress/egress channel should be deep enough to maintain year-round flow. Connecting the ponds to the river on the upstream section of the mine should be avoided because this may encourage the river to avulse into the pit at an accelerated rate.

Miners need to obtain a Hydraulic Project Approval issued by the Washington Department of Fish and Wildlife if mining plans involve a constructed connection to a river or smaller stream.

**EXAMPLES OF OFF-CHANNEL HABITAT CREATED BY RECLAMATION**

**Weyco-Briscoe Ponds on the Wynnoochee River**

Many gravel pits are located along the Wynnoochee River, which drains the Olympic Mountains (Fig. 6). The Weyco-Briscoe ponds, in sec. 22, T19N, R8W, river mile 17, are examples of small ponds excavated for gravel that have been converted to off-channel habitat (Fig. 7). Using natural pond characteristics identified by Peterson (1985) as a guide, the company constructed ponds that provide shallow areas for food production, deep water for cover, and few perching areas for predatory birds. Because of the location, size, shape, and depth of the ponds, avulsion or stream capture is not likely to cause drastic environmental changes to the river (Collins, 1997).

Six ponds were created over a period of seven years during the 1980s. All are generally less than 20 ft deep, approximately...
0.5 to 1.5 acres in area, and connected to each other (Partee and Samuelson, 1993). On the downstream end, the ponds join the river to allow fish passage.

The ponds have been monitored since 1989 by Grays Harbor College to determine the extent of chum salmon spawning and use by other salmonid juveniles for overwintering. Monitoring of the site in 1990 indicated that the average immigrant coho fingerling was 49.6 mm long and weighed 1.20 g and the average immigrant chinook was 66.52 mm long and weighed 2.36 g. In contrast, the average Wynoochee River coho fingerling was 30.38 mm long and weighed 0.38 g, while the average chinook was 41.25 mm long and weighed 1.30 g. Immigrants into the ponds in 1990 included 1,249 coho and 146 chinook. Only 2 chum were recorded immigrating into the ponds in 1990. However, there were 73 juvenile chum emigrants that had spawned in the Weyco-Briscoe ponds (Grays Harbor College and others, 1990).

Initially, minor amounts of woody debris were placed in the ponds; however, Don Samuelson of Grays Harbor College considered this sparse cover to be a factor that limited use by and survival of salmon (Samuelson and Willis, 1995). In 1995, tons of woody debris were hauled to the site and placed in the ponds (Fig. 8). The ponds are being monitored to determine the results. From November through December of 1997, 31 chum adults and 66 coho juveniles immigrated into the ponds. Only 8 juveniles emigrated during this time period. Seven steelhead juveniles immigrated, and none left. Fish biologists also counted the carcasses of 69 adult chum in the ponds (Samuelson and others, 1997).

**Gravel Pits on the Humptulips River**

During the 1980s and early 1990s, gravel mining took place along the Humptulips River, which drains the Olympic Mountains (secs. 8 and 17, T20N, R10W), about 1/4 mi upstream of the U.S. Highway 101 bridge (Fig. 6). The gravel pits are no deeper than 30 ft and consist of about 20 acres of ponds (Fig. 9). Connections to the river were created by the mining company after mining had ceased. No woody debris was placed in the ponds, so there is minimal cover. The ingress/egress channel to one of the ponds dries up in summer. However, a well-vegetated riparian zone is now established along much of the ponds’ perimeter, and salmon usage is generally high during the winter. No further reclamation is planned.

A local salmon club now uses one of the ponds for a rearing pen. The other ponds are unmanaged and left open for salmon spawning and off-channel habitat. No quantitative monitoring of the site has been done, but Jack Ljestfield (WADFW, oral commun., 1994) believes the ponds support both salmon spawning and off-channel habitat for juveniles. Adult salmon are readily observed in the ingress/egress channels.

**Yakima River at Union Gap**

The Edler gravel ponds operated by Len Sali of Columbia Ready Mix, Inc., near the town of Union Gap are currently being mined with the intent of providing fish and wildlife habitat as a subsequent use. The ponds are located approximately 500 ft west of the Yakima River (Fig. 10). The reclamation plan is to finish mining with four ponds no deeper than 25 ft and covering an approximate total of 30 acres. Individual ponds...
will be connected to each other by sinuous channels as mining is completed, mimicking natural conditions. The first pond that was mined has been reclaimed (Fig. 10) and is no deeper than 18 ft. The southernmost pond, the last to be excavated, will be connected at final reclamation to the Yakima River by a channel that will provide fish access to the pond system.

All the ponds will be excavated to final slopes of 5:1 at the water edge. Where natural vegetation (trees and brush) exists adjacent to the excavation, Sali has selectively trenched to construct islands with established vegetation, which provides a seed source and increases the speed of final reclamation. There is deeper water in predator trenches developed around islands. Slopes above water will be no steeper than 3:1 and have the topsoil respread and grasses and native plants re-established. Topsoil stripped from the second pond area was replaced around the first pond mined, as required in the segmental reclamation plan. All four ponds will ultimately have irregular shorelines and varied depths. Approximately 25 percent of the ponds’ complex shoreline has water 2 ft deep, following the recommendations of regulatory agencies (Norman and Lingley, 1992; Norman and others, 1996).

Avulsion occurred in 1971 at gravel pits immediately downstream of the Edler site (Dunne and others, 1981; Dunne and Leopold, 1978). If avulsion or stream capture occurs at the Edler pits, the off-channel habitat would be lost, but the mining company and regulatory agencies anticipate few negative impacts on the Yakima River because the pit lakes emulate abandoned channels and are not overly wide or deep relative to the river.

While the Washington Department of Fish and Wildlife specialists expect that fish and wildlife use of the ponds will be high, the agency has no plans at this time to monitor the effectiveness of the reclamation or the plan that is being implemented.

**RECOMMENDATIONS**

Digging more ponds for off-channel habitat may be counterproductive in some reaches, and the ponds are not likely to outperform the natural system. Creation of off-channel habitat for salmon should be firmly coupled with plans for long-term monitoring to determine its effectiveness. Currently, the only gravel pit lakes that are monitored for off-channel habitat are the Weyco-Briscoe ponds. Department of Natural Resources reclamation specialists recommend that government agencies, tribes, academia, and industry collaborate in monitoring existing and future sites. Sites should be evaluated by a multidisciplinary team to determine the success of planned habitat and thereby improve future efforts.
ACKNOWLEDGMENTS

Funding for this project was provided by the U.S. Environmental Protection Agency (USEPA) through the Tri-State Agreement of Oregon, Idaho, and Washington to share and develop technical information regarding mining. I thank Nick Ceto and Bill Riley (EPA) and Jack Ljestfield (WADFW) for helpful discussions. I thank the following for discussions and their reviews and comments: Peter Wampler and Frank Schnitzer, Oregon Department of Geology and Mineral Industries; Ray Lasmanis, Lorraine Powell, Stephanie Zurenko, Rex Hapala, Jeff Cederholm, Larry Dominguez, Washington Department of Natural Resources; Don Samuelson, Grays Harbor College, Ken Bates (WADFW); Al Wald, Washington Department of Ecology; and Beth Norman, Pierce College. I thank Jari Roloff for help with editing and graphics and Keith Ikard for drafting Figure 6.

SELECTED REFERENCES


Figure 10. A pond in a part of the Edler sand and gravel pit near Union Gap south of Yakima shortly after reclamation and planting with native species (chiefly willows and cottonwood). The island in the background is in the center of the lake. Trees in the far background are on a reclaimed shoreline and are part of an undisturbed riparian zone. Shoreline slopes are less than 5:1. The 2- to 5-acre pits at this site were designed with islands and shallow shorelines to enhance fish and wildlife habitat. The miner replaced topsoil in and around the ponds to promote revegetation. The last pond to be mined will be connected to the Yakima River by a 20-ft-wide channel.

Grays Harbor College Research (Samuelson, Don; Phipps, James; Phillipi, Scott; Wargo, Lorna; Willis, Elizabeth; MacMillan, Norbert; Cornell, David; Mikkelsen, Nels), 1990, Physical, chemical, and biological characteristics of Weyco-Briscoe gravel pit ponds (July 1989–June 1990); Annual report: Grays Harbor College [under contract to] Grays Harbor Planning and Building Department, 1 v.
Petterson, N. P., 1982a, Immigration of juvenile coho salmon (Oncorhynchus kisutch) into riverine ponds: Canadian Journal of Fisheries and Aquatic Sciences, v. 39, no. 9, p. 1308-1310.
BOOK REVIEW: Collecting the Natural World—Legal requirements and personal liability for collecting plants, animals, rocks, minerals, and fossils

by Donald Wolbery and Patsy Reinard
Geoscience Press, Inc.
PO Box 42948, Tucson, AZ 85733
1997, $24.00

This book presents summaries of federal and state laws regarding collecting archaeological, botanical, biological, and geological items. Few entries are more than a page long, but the essence of each regulation is set forth. Federal land ownership and management are briefly described. The authors evidently recommend cautious use of their book. The disclaimer in small print on the back of the title page states: “This book is an interpretation of relevant state and federal statutes, a subject which is a constantly moving target. Therefore, it is entirely possible that a particular law has been missed or misinterpreted or has changed...the reader is directed to contact the agencies listed for more detailed information.”

Several appendices take up more than half of this 330-page book. These cover state symbols, fossils, flora, and fauna; addresses for various agencies; lists of national parks and monuments and when they were established; and the texts of the Antiquities Act of 1906, Historic Sites Act of 1935, Archaeological Resource Protection Act of 1979, and Federal Endangered Species Act of 1973 (with list of species). One of the appendices is titled “Using basic instruments [tools], maps, and leases.” In this section, the authors provide a sample lease form that might be used to arrange access to private lands. But they also recommend getting thorough legal advice about leases to avoid situations similar to what followed discovery of the infamous “Sue” tyrannosaurus. Paleontologists should be aware that at least 13 acts now affect collecting on federal lands, and other legislation is pending.

When contacted in July 1998, state offices had a somewhat different message for persons interested in collecting:

Washington’s State Archaeologist Rob Whitlam encourages potential collectors to go to the Internet for current regulations and contacts. The office urges a conservation and preservation ethic: Take only photos and try not to leave footprints.

In Washington state, no permits are required at this time for fossil or mineral collecting on lands managed by the Department of Natural Resources (DNR), but as a courtesy, contact Ellis Vonheeder at DNR’s Resource Planning and Asset Management Division, Materials Management Section (360-902-1618).

The Washington Department of Fish and Wildlife requires a permit for collecting on land it administers.

Washington law (RCW 79.01.748) states: “Every person who willfully commits any trespass upon public lands of the state and...digs, quarries, mines, takes, or removes therefrom any earth, soil, stone, mineral, clay, sand, gravel, or any valuable materials, shall be guilty of larceny.”

A general rule then is: To avoid trespassing, get permission and up-to-date information about regulations from the landowner (federal, state, or private) before you set out. The legal complexities and case law call for keeping current.

Despite the fact that this is a 1997 book, readers should be aware that there are typos and slips. Further, addresses given in the appendices may be out of date. For example, Washington’s Historic Preservation Officer can now be reached at PO Box 48343, Olympia, WA 98504-8343; the office is in Lacey, Wash. There is no longer a DNR Division of Lands and Minerals. It has become the Resource Planning and Asset Management Division, PO Box 47014, Olympia, WA 98504-7014. Look in your local phone book for information about locations of federal or local government offices as well.

This book is only an introduction to the fuzzy world of legalities in collecting. It might be a useful (though flawed) reference book for libraries, but it is not a comprehensive guide. The disclaimer says it all. Caveat emptor.

Kitty Reed
INTRODUCTION

Tailings are mine mill waste products consisting of ground rock from which the valuable minerals have been extracted. Due to inherent chemical and slope instability and other potential environmental problems, they can represent long-term public and private land-management challenges. For example, precious metal tailings may contain dissolved metals and cyanide complexes (Miller, 1997). If the tailings impoundment is poorly designed, constructed, or reclaimed or is breached or otherwise loses its integrity, release of contaminants and sediments can threaten the environment. In response to these potential problems, state and federal agencies and local government have steadily increased environmental scrutiny and regulation of metal mine tailings since the early 1970s.

Modern tailings impoundments that are properly designed, sited, constructed, maintained, and reclaimed are unlikely to cause acute environmental problems. At many metal mine sites, the single most important environmental issue is the quality of reclamation of all the mine’s components, including waste rock dumps, the mine itself, and the tailings facility. There can be no high-quality reclamation without considering all aspects of a tailings facility.

TAILINGS CHARACTERISTICS

Tailings are generally composed of fine sand- or silt-size particles, typically deposited as a slurry, and, depending upon the method of deposition, may be graded so that coarser material is nearer the point of discharge. Gradients in grain size occur both vertically and horizontally.

At most mines, some of the metals in the mined material cannot be recovered in the mill and are discharged to a tailings disposal facility (TDF). In older tailings or where gangue metals are not economic, the metal content can be 10 percent or higher due to milling inefficiency. Many modern mining operations achieve metal concentrations of less than 1 percent in tailings (Williamson and others, 1982). However, at some mines, it is not the metal with economic value that is problematic, rather it is the associated metals that reach toxic levels.

Due to variations in milling, original mineralogy, and deposition method, tailings can have high salt contents, be acid or alkaline, have macronutrient deficiencies, display particle-size stratification, and lack organic matter (Munshower, 1994). Other sources of toxicity are processing agents, catalysts, reagents, and chemicals that are not recovered in the mill and thus are discharged to the TDF. Cyanide is the most toxic reagent commonly used in metal recovery, but it degrades quickly when exposed to air. At most modern mine operations, tailings are routed through a cyanide destruction and detoxification circuit before discharge to the TDF. Cyanide destruction methods, which can also be toxic, are discussed in Denton and others (1992), Smith and Mudder (1991), and Norman and Raforth (1995).

To minimize toxicity of tailings, mine planners must consider original rock chemistry, including metal and sulfide content, in reclamation. In addition, revegetation success on tailings is influenced by chemical and physical changes introduced by the milling process.

LOCATION AND CONSTRUCTION OF TAILINGS IMPOUNDMENTS

Because the ultimate success of tailings containment and isolation depends on the long-term stability of the impoundment dam itself, a description of impoundment types is warranted. Tailings impoundments (dams) can be broadly classified as follows:

- valley containment, where a dam is constructed across the valley,
- level ground impoundment, with ring dike containment and tailings deposited in the center, and
- sidehill impoundment, which relies on a dam constructed with three sides.

The rugged topography in Washington metals mining districts generally dictates that the impoundment design be either valley or sidehill containment (Fig. 1). Currently, mining companies tend to use mine waste material for impoundment construction. Waste rock can be used for the main portion of the embankment if the rock is of suitable construction quality and will not generate acid rock drainage. Clean sand and gravel, if available from the overburden, has also been used. Generally, the embankment is constructed in 2- to 8-ft-thick lifts and compacted. Some mine operations outside of Washington use cyclones (cone-shaped devices that have no moving parts) to separate the coarse fraction from the fines by centrifugal force; the sediment is discharged at relatively low moisture content through the bottom. The coarse sands can then be stacked to form the sand portion of various embankment types. The overflow, or fines, is discharged to the tailings pool away from the sand embankment.

Most tailings dams in Washington are low-permeability water-retaining structures. Tailings dams that can impound 10 acre-feet or more of water measured from the dam crest must meet state dam safety standards. The Washington Department of Ecology’s Dam Safety Section regulates planning and construction of dams under Revised Code of Washington (RCW) 90.03 (The Water Code) and RCW 86.16 (The Flood Control Act).

TDF dams are generally constructed using the downstream, centerline, modified centerline, or upstream method (Fig. 2). The downstream method requires the most material, covers the...
largest area, and is the most expensive to build. Figure 3 shows a completed downstream method TDF. The downstream method results in TDFs that are generally more stable than dams constructed using other methods, and the integrity of any geomembrane (low-permeability synthetic) liner can be easily maintained. Costs for the downstream construction method may be reduced if suitable material is available on the mine site. In areas that may be subjected to large seismic events, the downstream method is the most stable. The upstream method uses the tailings as its base as each lift is added. It is the least expensive to build and the least stable (Gipson, 1998). The centerline method shares both advantages and disadvantages of upstream and downstream methods.

Construction methods can affect tailings discharge management. Valley or side valley containment is more effective than stacking tailings on level ground. Discharge from a valley containment system is normally confined to one point, and seepage is fairly easy to collect. Reclamation of a valley-contained TDF is simpler than for a ring dike TDF because long-term surface drainage can be more readily re-established (Welch and Firlotte, 1989).

TAILINGS SITE SELECTION

Site selection for an impoundment must take into consideration the position of ore bodies, distance and elevation from the mill, watershed characteristics, existing and future land uses, site geology, environmental concerns (such as water quality, dust control, vegetation, and wildlife), property ownership, proposed type of closure and reclamation, and the overall costs of the project. In Washington, the siting criteria for tailings impoundments are set forth in the Metal Mining and Milling Act (RCW 78.56.090). The mining company may propose several sites, or the Department of Ecology may select a site. The Department of Ecology must issue a site selection report for the agency’s preferred location for the TDF. The report must analyze the feasibility of reclaiming and stabilizing the tailings; it must also take into account the objectives of the mine proponent’s application relative to mining and milling operations. RCW 78.56.090 states “these objectives shall consist of, but not limited to (a) operational feasibility, (b) compatibility with optimum tailings placement methods, (c) adequate volume capacity, (d) availability of construction material, and (e) optimized embankment volume.” Siting criteria are qualitatively based on proximity to the 100-year flood plain and surface and ground water, topographic setting, geologic hazards such as landslides and active faults, visual impacts, soil, geotechnical, and hydrologic characteristics.
LINERS

A liner system helps minimize the chances of leakage from the tailings into ground water or surface water. Historically, liners (soils, clays, and geomembranes) have failed and leaked, but recent advances have made liners far more reliable. Mine location, environmental considerations, and state laws or regulations help determine the type of liner to be used in tailings facility construction. Further, liner design must be based on the assumption that leaks will occur and that leak detection and recovery systems are necessary.

If a site lacks adequate natural materials such as clay, sand, and gravel to construct liner components, a synthetic liner system must be used. Typically, multiple liners are required, and the bottom layer consists of clay or amended soil material. Nonetheless, the mining company, agencies, and third party consultants should regularly conduct careful reviews of construction-quality assurance/quality control (QA/QC) (Norman and Rafforth, 1995).

Important considerations in choosing material for soil liners are availability and composition. In general, increasing the clay content of the liner material decreases the permeability. The liner material must have an appropriate amount and type of clay to achieve low permeability, high plasticity, and chemical stability when in contact with the tailings, which may contain cyanide, metals, acids, or other reactive solutions. Material for soil liners can consist of on-site or local borrow materials (if they have the correct clay content), bentonite, or mixtures of both. Imperfections such as roots must be removed during construction of the liner system.

The thickness and method of liner compaction are engineering considerations. Most clay liners are designed to achieve a hydraulic conductivity (permeability) in the range of 10⁻⁶ to 10⁻⁷ cm/sec (1.0 to 0.1 ft/yr). To attain low-permeability containment, clay liners must be thoroughly mixed, conditioned, carefully placed, and properly compacted, as well as protected against damage to continuity due to cracking from drying and shrinking (Hutchison and Ellison, 1992). Expandable clays (smectite and illite-smectite group clays) are less permeable than other clays (kaolinite or illite) and are more commonly used.

Impoundments have used synthetic liners since the 1940s. Technological advances in the manufacture of synthetic materials during the past decade have resulted in the widespread use of geomembranes for all components of the liner system (Ellison and others, 1992). Geomembranes are made of polyvinyl chloride (PVC), Hypalon™, high-density polyethylene (HDPE), very low density polyethylene (VLDPE), chlorinated polyethylene (CPE), asphalt/hydraulic asphaltic concrete (HAC) (Dorey and others, 1988), and XR-5 (chlorosulfinated polyethylene) (Marcus, 1997). The three most commonly used geomembranes are HDPE, PVC and VLDPE.

Geosynthetic clay liners (GCLs) are also commonly used. GCLs sandwich bentonite (composed mostly of smectite-group clay) between two geotextiles (woven or non-woven permeable synthetic fabrics) that are glued or sewn together. These liners have been used for the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) containment systems and covers for uranium mine tailings since 1988. They have the advantage of being easily placed, can be less costly than imported clays (if local clays are not available), and are tolerant of handling during installation. A drawback of GCLs is the loss of shear strength stability when they become hydrated and the potential for significant increase in permeability because of the high cation-exchange capacity of the bentonite (Richardson, 1994).

Important considerations in choosing geomembranes are thickness, strength, durability, cost, cover material needed for cushioning, the method of placement, and the construction method and quality of seams between the sections of the liner. The suitability of a geotextile material varies with the density achieved during manufacture (Ellison and others, 1992). In addition, geomembranes should not react with the reagents used in the milling process or in the tailings. The long-term life expectancy of geomembrane liners currently in use is not known but is shortened by exposure to sunlight. Most geomembranes are now manufactured with ultraviolet inhibitors and are expected to last more than 50 years even if exposed to sunlight.

In the past, tailings from mills using flotation-only circuits were deposited in unlined facilities. The mine operators relied on the perceived “relatively benign” nature and the low permeability of the tailings to minimize ground-water impacts (van Zyl, 1997). However, reliance upon these characteristics alone is not adequate to meet current water-quality protection requirements, which is another reason liners are required.

Water quality can be severely degraded if liners fail. Past failures of geomembrane liners have been attributed to poor welding of the seams or joints in the geomembrane or to puncturing during or after placement. Properly cushioning the geomembrane can prevent punctures. New techniques for welding seams have considerably improved seam reliability. Installing a cover layer to cushion and protect the geomembrane has also been key in successful operations. Indeed, most failures can be prevented by strict adherence to QA/QC during pad construction (Hutchison and Ellison, 1992).
Geotextiles are used above and below the geomembrane layer to protect against penetrations by underlying rocks or large particles due to loads from construction activities or the weight of the waste material. Protecting and cushioning the liner can be accomplished with clay- to sand-size material. Small rounded gravel has also been used successfully to protect geomembranes from puncture. The protective soil must be relatively free of large rocks and roots that could concentrate stress on the liner.

The preceding discussion indicates that liners must be designed on a site-specific basis. Common designs in use today consist of:

- two layers of synthetic material separated by a permeable leak-detection layer (sand or a permeable synthetic net);
- a lower layer of clay or clay-amended soil, a middle leak-detection layer of sand, and a capping synthetic layer; and
- a composite liner composed of a synthetic layer immediately overlying a clay or clay-amended soil layer.

**REQUIREMENTS FOR TAILINGS FACILITIES IN WASHINGTON**

In Washington, RCW 78.56 (Metals Mining and Milling Act) requires that tailings facilities be designed and operated to prevent the release of pollutants. Mine operators must apply “all known available and reasonable technology” to limit the concentration of potentially toxic materials in a tailings facility and to assure protection of wildlife and human health.

Tailings facilities must have a containment system that includes an engineered liner system, leak detection and collection elements, and a seepage collection impoundment to assure that a leak of any substance regulated under RCW 90.48 (Water Pollution Control Act) will be detected before escaping to ground or surface water. The design and management of the facility must ensure that any leaks are detected in a manner that allows for remediation pursuant to RCW 90.48.

Also according to RCW 78.56, applicants for metal mines and tailings facilities permits must submit a detailed engineering report about the facility design and construction to the Department of Ecology for review. If a dam is included, the Department of Ecology’s Dam Safety Section approves the design and construction, while the Water Quality Section approves the waste treatment system. Tailings facility design must take into account natural conditions, such as precipitation and depth to ground water, but not as a replacement for the protection required by the engineered liner system.

The goal is to reduce the toxicity of mine or mill tailings and the potential for long-term release of regulated substances to the greatest extent practicable through stabilizing, removing, or reusing the substances. When the tailings facility is closed, isolation and containment of potentially toxic materials is assured.

**Drainage Layers**

Drainage layers must be included as part of the engineered liner system required by RCW 78.56. Drainage layers are intended to maintain a low hydraulic head above the liner acting as the containment barrier. Traditionally, high-permeability sand or rounded-gravel drain layers on top of the liner drain fluid transmitted through or expelled from the low-permeability tailings to a collection pond for treatment, if needed. Several inches of free draining gravel and coarse sand are adequate in most places to rapidly remove the small volumes of fluid. However, mining companies generally place thicker (8–18 in.) layers of sand and gravel for the drain layer. The sand drainage layer is generally placed between an upper geomembrane layer and a lower geotextile layer that is intended to minimize clogging of the sand by the fine tailings. The drainage layer commonly includes a network of closely spaced perforated pipes that rapidly drain collected fluids and minimize hydraulic head above the liner.

Geonets (a net-like synthetic) have also been used as drainage layers within liner systems and allow effluent to be collected at a single point. Geonets are formed with a minimum of two layers of ribs oriented to enhance planar flow. Geonets are approximately 1/4 in. thick, and the structure of the net can provide the same planar flow capacity as a 12-in. layer of sand having a permeability of 10^-2 cm/sec (Richardson, 1994). Geonets have less hydraulic storage than conventional sand or gravel drains; this allows draining fluid to reach a monitoring and recovery point faster. Sand and gravel drainage layers can store a significant volume of water in their pore spaces. The thin geonets have almost no storage capacity, and liquid must be removed continuously, typically by a gravity drain.

**Leak Detection**

Leak detection systems for tailings impoundments have become commonplace at most metal mines and are required in Washington by RCW 78.56.100. Detection methods vary widely and may include monitoring wells, lysimeters, piezometers, neutron probes, dielectric probes, tracers, and underdrains that route leaking solution to a single point.

One of the newer methods of leak detection uses direct-current electrical resistivity. To locate leaks, an electrical current is generated and sent to the ground between two electrodes, one above the liner and the other in the soil or material below the liner. A grid of electrodes is also effective. If the geomembrane is intact, very little electrical current will flow through the highly resistive plastic liner. If a hole exists in the liner, there will be an increase in the electrical current flow at the point of leakage, which will create an anomaly in the electrical potential measurements (Bishop, 1997)

**WATER QUALITY AND GEOCHEMISTRY**

The primary water-quality issue associated with tailings is the potential for toxicity to humans, wildlife, and vegetation through degradation of surface water and ground water by solutions draining from the tailings. One source of toxicity is processing chemicals introduced during milling. Many mills employ cyanide leach processing in metal recovery. Although cyanide is toxic, it degrades quickly under oxidizing conditions. Some degradation byproducts, such as ammonia, are also potentially toxic, depending on the concentration and dose. Most operations employ an inline cyanide destruction circuit before the tailings are discharged to the impoundment facility. In many instances, the level of toxicity introduced by mill process circuits could be largely managed in the mill; this would cut costs and contribute to the goal of economic recovery of minerals. Pollution prevention involves using substitutes for toxic chemicals, reducing the amount or concentration of toxic chemicals used in processing, modifying processes, and improving housekeeping and maintenance (USEPA, 1995).
Another source of waterborne toxicity is the generation and release of acid rock drainage (ARD) from the tailings. Acid drainage results from the exposure of pyrite (FeS₂) and other metal sulfides to air, which causes oxidation and generation of acids and dissolution of metals mobilized by percolating water. Tailings that contain sulfides and insufficient buffering minerals are particularly susceptible to acid generation because finely ground material has a large available reactive surface area. Commonly, older mines deposited tailings in valleys (Fig. 4) or on slopes without designed embankments; at times tailings were dumped directly into streams, rivers, or lakes. Some modern tailings impoundment failures have resulted in uncontrolled discharges and released ARD and tailings materials (Steffen, Robertson, and Kirsten, 1989).

Mitigation of ARD is difficult and expensive. The greatest concern of regulatory agencies is that they will discover ARD after mine closure and abandonment when financial resources to fund mitigation are no longer available. At some mines, the buffering potential of tailings is chemically “used up” years after the tailings have been deposited, resulting in ARD. For example, at the Thompson Creek mine in Idaho, it took about 10 years after deposition for the tailings to generate ARD (Jerry West, Idaho Dept. of Environmental Quality, oral commun., 1998). Thorough study and laboratory testing of the acid generation and neutralization potential of the tailings are imperative if planning and design are to anticipate the ARD issue and avoid buffer depletion.

Current mining and regulatory objectives are to perform some level of investigation of the potential for acid generation before, during, and after mining. Pre-mining investigations should include multiple geochemical tests of the material expected to be placed in the tailings disposal facility. If these conservative tests suggest potential for ARD generation in the tailings, mitigating measures must be included in the milling circuit (for example, a system that removes sulfides) or the TDF design. If there is an ARD potential, regulators should anticipate the need for an engineered design that assures that long-term water quality will not be adversely impacted by discharges from the TDF. The engineered design should include not only containment and isolation of the tailings, but also a reliable method of treating post-closure water discharges. The mining company should estimate the costs involved in treatment facility design, construction, and maintenance. Innovative reclamation might include designs that will minimize oxygen diffusion and percolating water in the tailings.

Adequate baseline water-quality monitoring, including sampling of adits and pits near the site, is a critical element in mine planning. This information can supplement geological studies and predictive geochemical results. The mining company might construct a geological model of the area to explain observed variations in water chemistry and to estimate relative quantities of potentially acid-generating and acid-neutralizing rock. However, the duration of some tests may limit their accuracy in predicting the potential for ARD using various geochemical tests. Short-term tests are likely to be poor predictors of long-term geochemistry and can hamper attempts to quantitatively forecast impacts and costs. The test results resemble meteorological predictions in that, given certain conditions, one can only say that there is a higher or lower probability of acidic or alkaline water (Kleinmann, 1997).

Mine operators routinely analyze rock samples from the mine/prospect site to determine their acid- and alkaline-producing potential on the basis of percent sulfur or pyrite (Kleinmann, 1997). Valuable information can be gained by investigating nearby operations or abandoned mines if they are reasonable analogs of the proposed mine site. If nearby sites are acid-producing, the mining company should conduct intensive geochemical investigations during pre-mine planning as well as during mining and reclamation of the new site. The analytical methods commonly employed to predict ARD fall into the category of static or kinetic tests; those recommended by Price (1997) and Price and others (1997b) for a metal leaching/ARD prediction program are:

**Static tests**

- trace-element content (total and soluble concentration)
- acid-base accounting
- total-sulfur and amount of sulfate and sulfide
- bulk neutralization potential
- carbonate neutralization potential

Figure 4. Copper mine tailings in the valley of Railroad Creek above Lake Chelan, Wash. Tailings from the Holden mine were deposited in the valley bottom in the 1940s and 1950s. The tailings have generated acid rock drainage and have also been eroded by the stream and interacted with ground water beneath the tailings. The Washington Department of Ecology, U.S. Forest Service, U.S. Environmental Protection Agency, and Alumet, the parent company of Howe Sound Mining Company that originally mined at Holden, are now cleaning up the site. Because no vegetation was established, blowing dust was a chronic problem. A gravel cover has now stabilized the surface, and revegetation may be easier. Test plots showed that revegetation is possible on these acidic tailings; lupine and Sitka alder, plants native to the area and nitrogen fixers, were the most successful plants in the test plots monitored by the Forest Service (Scherer and others, 1996).

(Photoby Eric Schuster, Washington Department of Natural Resources.)
Kinetic tests of reaction rates and drainage chemistry

- pH
- mineralogy and other geological properties
- petrographic examination
- pre- and post-weathering characterization
- humidity cell
- on-site pilot tests of tailings
- mine wall washing stations (performed in-place on the rock face)
- site drainage monitoring

The recommended kinetic test is the humidity cell, used for predicting primary reaction rates under aerobic weathering conditions (Price and others, 1997a). In theory, kinetic tests reflect the difference in rates of sulfide oxidation and of calcium carbonate dissolution reactions. Whether this makes kinetic tests more realistic is difficult to say, due to general lack of field verification. In contrast, static tests only indicate relative chemical activity among minerals but are not time dependent. An additional problem shared by static and kinetic tests is that their relevance is limited by the degree to which the samples being tested are truly representative of the mine or waste compositions (Kleinmann, 1997). In the case of tailings, representative samples are generally easier to obtain because ores are blended during grinding and milling.

However, Price and others (1997b) suggest the following factors should be considered when predicting the future drainage chemistry of tailings:

- The composition of tailings may change considerably over time. Milling procedures used by metal mines can remove sulfides and add alkalinity, both of which reduce the metal leaching/ARD potential. However, other milling practices can increase the potential for metal leaching/ARD by adding metal-bearing reagents like copper sulfate. The metal leaching potential will depend on the mill process, pertinent mineralogy of the ore, and particle size.

- Tailings have fine grain sizes and thus have a large surface area; all mineral components are readily available to weathering processes.

- Fine tailings have a reduced pore size and thus lower permeability for both air and water. Restricted air movement may limit the rate of oxygen replenishment, thereby reducing acid generation and metal leaching and perhaps changing the balance between acid generation and neutralization.

- Significant mineralogical and particle-size segregation may occur when tailings are deposited. Selective deposition of heavy minerals may create zones that have higher metal-leaching potential and are close to the deposition point. Separation of sulfides or carbonates on tailings beaches may result in localized ARD.

Specific needs in designing tailings disposal are:

- a milling and metallurgical study of how to remove sulfides and add alkalinity and of the effects of adding or removing metals to determine the effect of these tactics on the metal leaching and ARD potential, and
- regular operational sampling and analysis of tailings to confirm pre-mining material characterization.

The study should cover the range in ore composition and identify the milling process, pertinent mineralogy, and particle size that most effectively eliminates or minimizes ARD. In tailings, which tend to be more homogenous than waste-rock dumps, predictions of water quality tend to be more reliable. At 16 sites studied by Environment Canada, no site with a calculated excess neutralization potential produced acidic drainage (Kleinmann, 1997).

**DISPOSAL METHODS**

Tailings are conventionally deposited as a slurry moved in a pipeline (by gravity or pumping) and delivered to a fixed or moveable single point in an engineered surface impoundment (Fig. 5). This process can place the tailings in fairly thick layers and, while excess water is typically decanted from the surface, tailings can remain saturated for years if not dried before new layers are deposited. Reclamation must wait for the surface layer to dry enough to safely support earthmoving equipment (Fig 6). Lower layers either remain saturated or eventually drain out the bottom of the impoundment.

While deposition as a slurry directly to an impoundment is still the predominant method of tailings disposal, modified slurry methods or several other techniques are gaining acceptance and becoming more widely used. These include dewatering, paste, and air-dried deposition. Under some circumstances, these alternative methods result in higher quality and less costly reclamation as well as greater mine efficiency.
High-quality reclamation depends on key engineering techniques such as good dam integrity, covers that are nontoxic, and permanent vegetation, all of which result in water quality that is appropriate to beneficial post-mining uses. Options other than conventional slurry deposition that allow for earlier and better reclamation must be considered, especially if they result in less impact to the environment by lowering the potential for release of metals to ground or surface waters. Today, alternative disposal methods are drained and air-dried, submarine, thickened, and paste.

**Drained and Air-Dried Method**

Mining companies use drained and air-dried (subaerial) methods extensively in arid environments such as Nevada. The method involves sequencing the deposition of thin (<4 in.) lifts of tailings in segments of the impoundment so as to allow previously deposited lifts to dry and consolidate (Knight-Piesold Co, oral commun., 1998). These impoundments must have enough surface area to allow time for drying in one or more parts while deposition continues in other parts; tailings must be deposited over at least two segments for this method to be successful, and as many as 28 segments have been used. The selection of number of segments is based on the climate, tailing production rate, tailing drying characteristics, and facility shape (Gipson, 1998).

In arid climates, desiccation proceeds under high evaporation rates. This reduces the moisture content of the material, while increasing the density and shear strength. Drying allows a fairly strong crust to form, but this crust may crack as a result of shrinking (Newson and others, 1997).

The drained and air-dried method offers the advantages of improving control of the amount and chemistry of the solution within the facility and developing a stable, denser tailings deposit that has a lower moisture content. The tailings are easier to reclaim because they are not saturated and loose. The increase in density resulting from drained and air-dried deposition permits nearly twice the amount of tailings to be stored in the same volume of tailings facility as an undried slurry (Gipson, 1998). Some companies using this method are Battle Mountain Gold Corp. (San Luis mine, Colo.) and American Barrick Resources Corp. (North Block tailings facility, Twin Creek mine, Nev.). (See also Fig. 5.)

**Drum Test**

The standard slump test is described in ASTM C143. Slump is defined as the height lost when a filled cone 12 in. tall, 8 in. wide at the base, and 4 in. wide at the top is slowly lifted off a plate and the cone contents are allowed to “slump”. A 7-in. slump = the initial 12 in. height − 5 in. height lost.

**Submarine Tailings Disposal**

Tailings have been placed via discharge of a slurry at a submerged outfall in lakes and marine water typically more than 150 ft deep. One objective of this disposal method is to place tailings where ambient dissolved oxygen concentrations are minimal, thus reducing the potential for metals to be oxidized, mobilized into the water column and made biologically available, or transported away from the site of deposition. Other objectives are to place tailings in a stable environment and to prevent fines from entering the shallow, biologically productive euphotic zone (Rankin and others, 1997).

Examples of submarine tailings disposal operations are the BHP Island Copper Mine at Rupert Inlet, B.C.; Kitsault Molybdenum Mine at Alice Arm, B.C.; Black Angel lead-zinc mine at Maarmolik, Greenland; and Misima gold-silver mine in Papua New Guinea (Rankin and others, 1997). Mine operators believe that submarine disposal is an ecologically acceptable alternative to land-based tailings disposal. Environment Canada and Canada’s Department of Fisheries and Oceans have initiated a review of the ecological issues (Rankin and others, 1997).

However, it is not likely that submarine tailings disposal would be used in Washington as this is not allowed by either federal or state law. Thresholds for metal content would probably exceed those allowed by current regulations. Additionally, Department of Natural Resources Aquatic Resources Division regulations (Washington Administrative Code 332-30-166 (1)) regarding submarine disposal state “Open water disposal sites are established primarily for the disposal of dredged material obtained from marine or fresh waters. These sites are generally not available for disposal of material derived from upland or dryland excavation except when such material would enhance the aquatic habitat.”

**Thickened Tailings**

Dry tailings, also called dewatered tailings, may not require a tailings impoundment. This method uses either a filter or a high-density thickener that relies on flocculation. Typical operations use a thickener and filter (such as a belt press) in combination or, increasingly, a thickener alone to produce a tailings consistency similar to a paste. Some mines use cyclones, belt filters, or other mechanical filter equipment alone to reduce moisture content in the tailings. Solids contents as high as 85 percent can be obtained from such devices (Johnson, 1997).

Each 6-in. layer of processed tailings is allowed to dry further prior to adding the next layer. Typically, the layers crack during drying, and the next layer fills the cracks and adds to the pile. Currently, dry stacking operations create high-slump, low-viscosity tailings that will flow easily as a thin layer over a wide area (Schoenbrunn and Laros, 1997).

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1 The standard slump test is described in ASTM C143. Slump is defined as the height lost when a filled cone 12 in. tall, 8 in. wide at the base, and 4 in. wide at the top is slowly lifted off a plate and the cone contents are allowed to “slump”. A 7-in. slump = the initial 12 in. height − 5 in. height lost.
have detrimental effects on ground water. At some sites, eliminating free water is available to generate a leachate that might little free-draining water (Cincilla and others, 1997; Golder Associates, 1996).

Examples of thickened tailings are at alumina plants such as Alunorte in Brazil, Alcoa of Australia’s plants at Pinjarra, Kwinana, and Wagerup, and Alcan’s plants in Jamaica, at Vau-dreuil in Canada, and at Aughinish, Ireland. Placer Dome’s La Coipa mine in Chile uses horizontal belt filters to create thickened tailings. After their tailings pond filled up, the Sunshine gold mine in Nevada used a belt press in conjunction with a thickener to create space for tailings from remaining ore reserves rather than add a lift to the dam (Schoenbrunn and Larsen, 1997).

Paste
Recent developments in dewatering equipment design have made practical the consistent production of tailings that have a low moisture content and distinct flow and water retention properties; these are commonly referred to as pastes. Pastes are dense, viscous mixtures of tailings and water that, unlike slurries, do not segregate when allowed to rest. Generally speaking, pastes resemble wet stiff concrete, and an optimum consistency for a typical paste would be in the range of a 7-in. slump. Terminology for concrete tests is used in the evaluation of pastes. Pastes consist of enough fine particles (at least 15% by weight passing the 20-micron size sieve) to allow them to flow through a pipe, yet have enough retained water to create a non-segregating mixture. However, the most important aspect of paste is that the largest portion of the entrained moisture is held by surface tension in the fine particle matrix. This phenomenon produces a material that has an initial moisture content in the range of 20 percent (by weight) and, like concrete, a noticeable lack of free-draining water (Cincilla and others, 1997; Golder Associates, 1996).

Pastes have distinct environmental advantages. First, very little free water is available to generate a leachate that might have detrimental effects on ground water. At some sites, eliminating free water during deposition could remove the need for an engineered water-retaining structure. Second, because it does not segregate, it can be pumped to a placement site. In addition, a few percent of portland cement or fly ash can be added to paste; this significantly increases its dry strength, durability, and ability to buffer acid tailings and can encapsulate particles that are potentially acid generating.

Surface paste disposal at the proposed Rock Creek copper mine project (currently in environmental review) at Noxon, Mont. (Fig. 7), would allow ASARCO to reclaim the tailings concurrently with mining (Young, 1997). Among the cited advantages of using paste for this project would be limiting the active areas of disturbance and eliminating the need for a surface water-impoundment, and thereby the potential for seepage through the deposit. The potential for earthquake-induced liquefaction would be low due to the low moisture content of the deposit. Because of the high density achievable with pastes, both the height and footprint of the TDF can be reduced for the same tonnage of tailings. Most significant, however, would be that final closure and return of the property to appropriate post-mining land use could occur shortly after paste production ceases (Golder Associates, 1996).

Pastes have been used extensively as backfill for underground mines. There is now interest in the potential of paste as an alternative to more traditional slurry tailings disposal methods (Cincilla and others, 1997; Golder Associates, 1996). Most rock types are amenable to paste production for surface disposal but may not be suitable for underground backfill. For example, high-sulfide content tailings with portland cement added have been used for underground backfill in Quebec to reduce the volume of surface tailings, strengthen underground workings, and minimize subsidence. But reaction between pyrite and free calcium ions produced by the dissolution of unstable portlandite hydrate (Ca(OH)2) can result in the precipitation of swelling secondary gypsum (CaSO4·2H2O) and very expansive ettringite (Ca4Al6[(OH)26](SO4)3(2H2O)), which produces a weak mortar not suitable for backfill (Ouellet and others, 1998). However, acid generation is probably less likely to occur in paste tailings because permeability is decreased and less oxygen can reach the minerals.

RECLAMATION AND CLOSURE
Dewatering and Shaping
Before beginning final closure and reclamation of a tailings facility where the slurry method was used, mine operators commonly must remove the water standing on the tailings (Fig. 8). Reclamation of saturated tailings can be difficult and costly. Final reclamation may have to be delayed until tailings have adequately dried (Fig. 9). An alternative method to surface air drying is the removal of pore water through vertical wick drains. These wick drains give pore water a fast path to the surface. Once drying has proceeded enough for equipment to work on the tailings surface, reshaping develops the planned.

Figure 7. Sketch of a proposed method of paste disposal at ASARCO’s Rock Creek project in Noxon, Mont., that will use a paste stacker to construct semicircular windrows (left side of the figure). Each lift (terrace) would be about 4 ft thick and allow for concurrent reclamation shown at the right of the figure. (Modified with permission from Golder Associates, 1996.)
drainage. Generally, drainage of the tailings should be coupled with control of storm water.

Covers

Cover designs depend on site-specific evaluations. Designing one cover that would be suitable for all tailings is not possible because of the wide range of climate, soil, and topographic conditions at mines (Ritcey, 1989).

Covers for tailings are generally either vegetation or a layer of soil, rock, or water. Under some circumstances abandoned tailings can be revegetated without applying topsoil. Abandoned mine tailings at Telluride, Colo., were revegetated by simply tilling organic amendments (manure and hay) and inorganic fertilizer into the surface (Redente and Baker, 1996). In virtually all instances, salvaging and replacing soil at operating mines would be less costly than amending tailings. For some abandoned tailings, the simplest covers used to stabilize the surface have been single or multiple layers of gravel. Where water layers have been used, no vegetation was established. Miners in British Columbia have used a layer of water to reduce the amount of oxygen entering highly acidic tailings.

Other cover designs have incorporated a gravel layer for drainage or a capillary break below the topsoil. Multilayer covers might consist of a top-to-bottom sequence of soil and gravel, infiltration barriers such as a geomembrane or a clay layer, and a geotextile (if required for support during construction). The U.S. Environmental Protection Agency (1989) recommends a multiple layer cover for hazardous waste such as uranium tailings.

Some tailings covers incorporate a barrier to prevent plant roots or animals from disrupting the integrity of the drainage and infiltration layers and burrowing animals from bringing contaminants to the surface. Typical biointrusion barriers are layers of cobbles or coarse gravel placed between the top layer and the waste (and infiltration barrier if present). This biointrusion layer can also be separated from soil by a geosynthetic filter layer (Henderson and others, 1992).

Mining companies have tried biointrusion barriers throughout the world for many types of hazardous wastes, mostly those associated with radioactive material. Bowerman and Redente (in press) evaluated studies documenting root intrusion where barriers had been emplaced. They conclude the ability of many kinds of barriers to protect against intrusion is questionable. For example, several plant species (such as crested wheatgrass, big sagebrush, and saltcedar) penetrated these barriers in moderately damp to arid environments. Harvester ants also managed to invade waste through gravel barriers. Mice, kangaroo rats, pocket gophers, and prairie dogs also breached the integrity of protective barriers.

At their Midnite uranium mine near Ford in northeastern Washington, Dawn Mining Company proposes a 15.3-ft-thick homogenous cover of sandy soil to protect water quality and control radon emanation. The site is characterized by sandy and sandy loam soil. Ponderosa pine woodland is the local late-successional native vegetation. The pines are 40 to 60 ft tall at the Midnite mine and can produce roots that reach depths as

Figure 9. Cannon mine tailings undergoing final reclamation in 1996 after 2 years of drying. Here a woven polypropylene fabric geotextile layer was laid down first as a supportive base on which to place sand and soil. A lower cover layer of 2.5 ft of gravelly sand was covered by an upper layer consisting of 2 ft of sandy silt pushed out onto the surface by small bulldozers. The surface was then prepared for revegetation by scarifying. Reseeding occurred the following fall and winter, and grasses are thriving. (See also Figs. 3 and 6.) (Photo courtesy of Asamera Minerals.)
Capillary Barriers

Capillary barriers of fine soil over coarse soil can be a simple, low-cost method of effectively limiting water and oxygen movement through the tailings cover (Stormont and others, 1996). In many settings, the capillary barrier functions as the drainage layer as well (Henderson and others, 1992). Capillary forces hold the water in the fine layer until it is removed by evapotranspiration or drains where the fine-coarse interface is sloped. A capillary barrier is effective if the combined effects of evaporation, transpiration, and lateral diversion exceed the infiltration from precipitation. However, if the fine layer becomes saturated, capillary forces will decrease and water will drain quickly through the fine layer into the coarse layer. Design considerations are unique to each site and must account for seasonality of precipitation and evapotranspiration.

REVEGETATION

Revegetation success generally depends on the cover design and tailings chemistry. For vegetation to be effective and healthy, the roots should be able to penetrate the soil and reach enough water that contains adequate nutrients and no toxic components. Metalliferous mine tailings commonly contain low concentrations of essential plant nutrients; nitrogen levels are invariably inadequate for plant growth (Williamson and others, 1982). Mining companies must conduct tests prior to and during mining to investigate the physical and chemical nature of the tailings and to determine if vegetation can be re-established. Important considerations are temperature, precipitation, wind, and aspect, as well as texture of the tailings. Direct revegetation of tailings without soils can be extremely difficult. An improved seedbed encourages germination and establishment of vegetation. Establishing vegetation on neutral tailings is less difficult than on nutrient-poor, salt-rich or alkaline or acid tailings. Over any acid-generating tailings, the soil layer, which is in many places topsoil and a mixture of subsoils, must be thick enough to prevent salt or acid migration to the surface. Acid tailings without soil coverings must be leached before seeding (Munshower, 1994). It may also be necessary to apply lime or some other neutralizing materials, as well as amendments such as manure, wood chips, compost, or biosolids.

Incorporating compost or biosolids and industrial wastes, such as fly ash, into acid-generating (or potentially acid-generating) tailings and mine waste has been effective. In Pennsylvania, for example, miners used coal fly ash to neutralize acid mine wastes and allow vegetation to be established (Scheetz and others, 1998).

In Washington, RCW 78.44 has required topsoil salvage only since 1993. It states ‘‘‘Topsoil’ means the naturally occurring upper part of a soil profile, including the soil horizon that is rich in humus and capable of supporting vegetation together with other sediments within four vertical feet of the ground surface.’’ This definition indicates that mine operators have to salvage more than just the “A” horizon for reclamation. If topsoil or amendments such as hay, biosolids, paper residues, or compost are available, revegetation of mine tailings is generally not a problem. Permanent stabilization of acid-generating tailings that are covered with a cap to establish a nontoxic rootzone can be accomplished with normal agricultural practices of seedbed preparation, fertilization, and seeding.

With a proper seed mix and soils amended with paper waste, which is widely available in the Pacific Northwest and other parts of the country, a lasting vegetative cover can be quickly established with little or no additional fertilizer application. Paper mill waste can act as both an amendment and a capillary barrier. Some of the advantages of paper mill residuals are low permeability, high water-holding capacity, low erosibility due to its fibrous nature, structure and stability suitable for root development, and neutral to basic pH to buffer infiltrating water before it reaches acid tailings. Canadian mining companies have successfully used paper pulp waste, a spongy, partially saturated material that absorbs large quantities of water, as a soil amendment for reclamation (Cabral and others, 1997, 1998). Paper mill sludges are composed of 40 to 60 percent organic material and have been “recycled” for successful use as landfill caps at several sites (Moo-Young and Zimme, 1995; Maltby and Eppestein, 1996; McGee and others, 1996).

At the East Sullivan gold-bearing massive sulfide mine in Val d’Or, Quebec, a 6.4-ft-thick cover of softwood and hardwood bark over acid-generating tailings effectively prevents oxygen from reaching the tailings. Biosolids from a municipal water treatment plant tilled into the first foot of the bark add nutrients (Tremblay, 1994). This site now supports a dense grass cover.

Re-establishing native plants at mine sites has become an important objective for reclamation. In many places, desired post-reclamation plant communities composed of native plant species are preferred because most are adapted to the climate and elevation of the site. Some native plants can out-compete some introduced (exotic) species over time and are more useful to wildlife. The vegetation at or surrounding the mine site can be used as a guide to selecting native species. Using native seed mixes or plants produced from locally collected seeds and cuttings and locally transplanted plants can greatly accelerate re-vegetation. If preplanning is sufficient and the appropriate tailings deposition methods selected, soil and native vegetation can be transferred directly from areas being stripped for mining to the TDF. This approach is less expensive and typically more successful than long-term soil storage. Soil hauled directly from a newly stripped area to a reclamation area carries with it viable seeds of native vegetation that can rapidly establish on the reclaimed area. This typically reduces the need for added seed and plant material (Norman and others, 1996). This method would be most appropriate at mines using paste deposition and concurrent reclamation.

Using Cattle as a Technique for Establishing Revegetation

At a mine at Miami, Ariz., miners have tried an innovative method of establishing vegetation on tailings (A. Throop, Oregon Department of Geology and Mineral Industries, written commun., 1996) (Fig. 10A,B). Where importing topsoil, seed-
ing, fertilizing, and irrigating had failed, penning cattle on the tailings piles was successful in encouraging vegetation. Generally, cattle trample and kill vegetation. In this case, the cattle trampled hay mulch, urine, and manure deep into the tailings and created terraces by their network of trails on the steep slopes. When compared to cattle not on tailings, the blood and tissue of these animals showed no toxic or unusual concentrations of trace elements (Dagget, 1997).

**Coarse Woody Debris**

Mining companies and regulatory agencies recognize the importance of replacing coarse woody debris on reclaimed areas (Harmon and others, 1986). At mine sites in the Pacific Northwest coarse woody debris is now incorporated in final reclamation. For example, a recently proposed mine will re-place stockpiled woody debris at approximately 7 tons per acre to provide a substrate for essential microorganisms. The company will salvage logs ranging from 10 to 24 in. diameter at their small end and at a variety of lengths longer than 6 ft. Furthermore, salvaged lichen-encrusted rock randomly distributed across the reclaimed areas will promote colonization by lichen (Battle Mountain Gold Co. and Golder Associates, 1998).

**CONSTRUCTED WETLANDS**

Wetlands are an effective means of improving water quality; coal mines in the eastern U.S. were the first to use wetlands in this context. Passive water treatment using constructed wetlands essentially simulates natural processes and is being used more commonly to treat mine water (Fig. 11). Bacterial reduction of sulfate and iron and precipitation of metal sulfides are important chemical processes in passive anaerobic treatment. Sulfide precipitates accumulate in the anaerobic zone and are not carried in the effluent (Filipek, 1997; Filipek and others, 1992; Sengupta, 1993). In a surface-flow aerobic wetland used to treat acid drainage, the dominant process is oxidation of iron and precipitation of iron hydroxides. Water in aerobic wetlands must be sufficiently alkaline to keep pH from falling as a result of the hydrolysis of iron. An anoxic limestone drain can be installed before water enters the wetland to add alkalinity and raise pH if no iron is present in the initial drainage (Filipek, 1997; Brodie, 1991). This type of wetland treatment works best if heavy metal concentrations are low.

**TRENDS**

Because mine operators and agencies now have a better understanding of the physical function of tailings and have improved techniques to reclaim them, tailings have become less problematic. However, tailings impoundments will require long-term monitoring to verify that they are not a source of contaminants.

Among recent trends in dealing with tailings are:

1. Regulatory controls are becoming more stringent, and mine operators are expected to rigidly adhere to them. Example of such control are Washington’s Metal
Mining and Milling Act (RCW 78.56) and Oregon’s Chemical Process Mining Act (ORS 517.952).

- Dry tailings deposition systems, such as dewatered, paste, or air-dried tailings, are reducing management problems.
- There is much wider recognition that intense geochemical testing early in mine planning is necessary to characterize tailings chemistry and to plan environmentally sound deposition.
- To achieve long-term physical stability of the impoundment, proper designs for closure more commonly consider long-term storm-water retention and seismic stability.
- An increased use of non-acid-generating waste materials for construction of mine facilities is reducing both disturbed areas and costs.
- Mine companies attempt to reduce cyanide levels to the lowest concentration consistent with technical feasibility and reliability to protect human health and wildlife.
- Contaminant monitoring programs and response plans are more widely required.
- Geosynthetic and clay liners have become widely accepted and are commonly used.
- Topsoil salvage and revegetation of tailings has become the norm.

ACKNOWLEDGMENTS

Funding for this project was provided by the U.S. Environmental Protection Agency (EPA) through the Tri-State Agreement of Oregon, Idaho, and Washington to share and develop technical information regarding mining. We thank Nick Ceto and Bill Riley (EPA) for helpful discussions regarding mining. We thank the following for discussions and their reviews: Allen Throop, Oregon Department of Geology and Mineral Industries; Jerry West, Idaho Department of Environmental Quality; Ray Lasmanis, Washington Department of Natural Resources; Rod Lentz, Okanogan National Forest; Brent Cunderla, Bureau of Land Management; Jeff White, Battle Mountain Gold Co.; Steve McIntosh, Echo Bay Minerals Co.; and Beth Norman, Pierce College. We thank Jari Roloff for help with editing and graphics.

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BOOK REVIEW: West Coast Fossils—A guide to the ancient life of Vancouver Island

by Rolf Ludvigsen and Graham Beard
Harbour Publishing
Box 219, Madeira Park, BC V0N 2H0
Paperback, $18.95 U.S. and Canadian

The many fans of the first edition of this fine guide will be glad to see the additions of major taxa to the record of fossils in an area just to the north of Washington. The preface to this edition indicates that there are now Carboniferous trilobites, a pterosaur, Cretaceous beetles, articulated fish (Triassic), and dinosaurs (a tooth), not to mention Middle Jurassic fossils and significant new finds of Mesozoic plant remains, all identifications vetted by current experts. Interestingly, credit for most of these discoveries goes to amateur paleontologists. And amateurs get thanks for helping save material at a Cretaceous plant locality.

To cover the additions, the book has been expanded to show examples of the new taxa. The many new (and high quality) photos augment the book’s clear and helpful information about identification as well as histories of the taxa. The remaining text is verbatim from the earlier edition, just slightly rearranged.

Readers who are not familiar with formation or geographic names can check out the helpful stratigraphic section on p. 43. That will make it clear that it is, for example, Protection Formation at Nanaimo, and Lambert Formation at Collinshaw Point; commas in the captions might help.

This revised edition appears only three years after the first. The authors deserve our thanks for bringing out the important new material so promptly. This book would be an excellent addition to the region’s libraries and to personal collections for its educational text as well as inspiration for a trip to Vancouver Island. The generalized geologic maps for the several periods represented on the island should make it possible to develop a rewarding itinerary.

Users of this thoroughly portable and well-designed guide will need little more than patience and sharp eyes to enjoy the hunt. Considering the sizes of some of the new finds, we need to travel with hand lenses at the ready. While the geology of Vancouver Island is not very like that of adjacent Washington, the message is clear: Go look. There is much yet to learn about former life nearly everywhere you go.

Kitty Reed

SUMMER INTERNS

We are fortunate to have two students from Community Youth Services working with us this summer. They have each done an excellent job for us, and we will be sad when their program is finished.

Myanh Tran is working as a clerical assistant this summer. She was born in Viet Nam, but has lived here for six years. Myanh will be a senior at North Thurston High School and is interested in the computer field. She plans to attend South Puget Sound Community College and the University of Washington.

MiMi (Melissa) Beach is working part-time in the Geology library and the rest of the time as a clerical assistant. She will be a sophomore at New Century High School. She is very interested in environmental science and hopes to make it a career someday.
In 1996, the Department of Natural Resources (DNR) established annual awards to recognize outstanding reclamation of surface mines. These awards honor permit holders who reclaim mines in an exemplary manner. Awards also recognize reclamation efforts on sites mined prior to 1971, before the Surface Mine Reclamation Act [RCW 78.44] became law.

The mines to which awards have been given demonstrate one or more of the following:

- Innovation in reclamation, such as creating unique wetlands, new approaches to enhancing wildlife and fish habitat, or imaginative shaping of topographic elements.
- Voluntary reclamation of mined land that is exempt from reclamation under the Act.
- Carefully planned and executed use of native plant species in revegetation.
- Innovative research and approaches to reclamation that can be applied at other mines.
- Attention to preserving water quality and preventing erosion.
- Orderly segmental mine development that results in high-quality reclamation.
- A consistent, long-term commitment to reclamation.
- Methods that enhance the environment and reduce reclamation liability, such as mining to a final slope.

Judges for the Division of Geology and Earth Resources Reclamation Awards for 1998 are:

Wayne Pederson, hydrogeologist, Washington Department of Ecology,
Brad Biggerstaff, engineering geologist, GeoResources,
Dave Mann, president, Washington Environmental Council,
Ray Lasmanis, manager, DNR Division of Geology and Earth Resources, and
Scott Nicolai, fisheries biologist, Yakama Indian Nation.

Division of Geology and Earth Resources Reclamation Award

Celite Corporation is the winner of the Division of Geology and Earth Resources Best Reclamation Award for their efforts at their diatomite pit in sec. 17, T18N, R23E, near Quincy.

Figure 1. Location of mine sites in relation to the nearest towns.

Figure 2. State Geologist Ray Lasmanis presents the DNR Reclamation Award to Bob Katsiouleris, Celite Corporation plant and mine manager, on May 21 at the site of the reclaimed diatomite mine. The crew responsible for this work looks on. From left to right are Aron Bennett, plant safety manager; Mike Wells, quarry maintenance; Bob Katsiouleris, plant and mine manager; Lane Wyman, quarry operator; Ray Lasmanis, State Geologist; Dave Norman, DNR Chief Reclamationist; Steve Vreeman, quarry operator; Gary Collins, quarry operator; Howard Vincent, quarry operator; Arlen Solders, truck driver; Gary Moore, quarry operator; Randy Rutherford, quarry operator; Louie Hoglund, quarry lead operator; Ron Massey, quarry operator. This auger scraper is used in reclamation of the pits; this machine can remove thinner layers of soils than a typical scraper without mixing or degrading poor-quality subsoils.
Figure 3. (Top photo) The Quincy operation before reclamation in 1971. These are the diatomite pits in sec. 17, T18N, R23E near Quincy (Fig. 1). The road in the foreground is also shown in the bottom photo. (DNR photo.) (Bottom photo) Most of the diatomite pits shown in this 1998 photo have now been reclaimed. Previously reclaimed areas have returned to sagebrush steppe through a natural floral succession. In recently reclaimed areas, the company planted grasses to stabilize the soils. (Celite Corporation photo.)
TOPSOIL

OVERBURDEN

MINERAL DEPOSIT

DIATOMITE

BACKFILL

TOPSOIL

Figure 4. Mining and reclamation sequence at the Celite mine. Topsoil, overburden, and diatomite are removed in separate steps so as to ensure reclamation success. After the diatomite is removed, pits are backfilled to approximately their original contours, then the topsoil is replaced and revegetated. This sequence of processes has led to high-quality reclamation. (Redrawn from Celite Corporation illustration.)

(Figs. 1, 2) in Grant County. Celite Corporation was nominated by Lorraine Powell, DNR Southeast Region Reclamation Inspector.

The company has reclaimed nearly 58 acres of this arid post-mining terrain to a high standard (Fig. 3). Segmental reclamation and separation and replacement of topsoil and overburden after the diatomite has been removed are the keys to their success. The work included voluntary reclamation of 13 acres exempt from state reclamation requirements because excavation there preceded enactment of the Surface Mine Reclamation Act.

Celite’s open-pit mining practices concurrent reclamation that involves salvaging topsoil and stripping caliche and basalt from above the diatomite deposits (Fig. 4). All salvaged overburden is segregated and preserved for backfilling and reclamation. Topsoil is re-spread over the mined area, fertilized, and seeded. The re-established topography approximates the original contours and blends well with the surrounding area. This level of reclamation is well beyond requirements of RCW 78.44.

Successful revegetation has stabilized the mined areas. In many places, one cannot tell the difference between undisturbed land and reclaimed land. All of the judges were particularly impressed with this outstanding effort.

Corporate Responsibility

Celite Corporation is a worldwide mining and minerals company and a leading producer of filter material and mineral fillers. The corporate headquarters are in Lompoc, California. Concerted reclamation of the depleted diatomite mine areas began with Celite’s acquisition of this mine in 1991. The managed transition from mining to reclamation modified all phases of mining here to reflect Celite’s policy of corporate responsibility in mine planning, operations, and restoration. Today, Celite begins every mine project with careful reclamation planning that is part of the strategy for opening a new pit, mining, and backfilling. Reclamation continues with monitoring and maintenance long after topsoil has been replaced and seeded.

Diatomite

Diatomite is made up of the empty shells or frustules of diatoms (Fig. 5), now the dominant photosynthetic organism in

Figure 5. Scanning electron micrograph of diatoms from the Celite pits. These algae have many more shapes than the “pill box” type shown here. Magnification is about 500X. The diameter of one of the diatoms shown in the center is 70 microns. (Celite Corporation photo.)
most of the world’s aquatic environments. More than 5,600 modern species of these single-celled golden brown algae, a type of phytoplankton, are known. Individuals of the larger species are barely visible without a magnifying glass. Most frustules are round, but some are elongated or branched or triangular.

Diatoms first entered the geologic record in marine upper Lower Jurassic rocks (Harwood and Nikolaev, 1995); they very rapidly increased in both diversity and abundance and are common in some mid-Cretaceous rocks. The oldest known continental diatoms are middle Eocene (Bradbury and Krebs, 1995). By the Miocene, diatomites had become common in the western United States. Local development of species is a common feature in large Tertiary lakes.

In Washington, diatom remains slowly settled to create thick layers on the bottoms of lakes that repeatedly developed on the surface of the Miocene basalt flows. These deposits are brilliant white and friable. The diatoms were able to obtain the silica needed for their shells from these volcanic rocks. Geologic evidence shows that some of these lakes dried up prior to another outpouring of basalt during the Miocene; in other lakes, the advancing lava flows cooled as basalt pillows.

Diatomite is used for filtration in food processing, rendering, and in making wine, beer and juices and as mineral fillers, coating agents, and carriers.

**Division of Geology and Earth Resources Good Neighbor Award**

Echo Bay Mineral Co. is the winner of the Good Neighbor Award. Echo Bay Minerals has made tangible contributions to numerous local events and groups. This company has donated money to Republic and Curlew high schools and the local library and has supported and made funds available to many community functions. For several years, the company has made Arbor Day a special event. Federal, state, and local government agencies and Echo Bay Minerals have joined forces to created a unique learning experience for hundreds of local fourth graders. The children learn about erosion, tree planting (Fig. 6), water pollution, impacts of trails and roads, fire fighting, reclamation (Fig. 7), fish and wildlife habitat, and other aspects of taking care of the environment.

**Corporate Responsibility**

Echo Bay Minerals Co. has maintained good community relations over the years. The company has continued to perform outstanding reclamation and remained a loyal, involved neighbor despite a severe down-turn in the price of gold.

**Division of Geology and Earth Resources Reclamationist of the Year Award**

Harlan “Bummie” Stoken (Fig. 8) is the winner of the Reclamationist of the Year Award. Mr. Stoken is a heavy equipment operator for Northwest Rock, Inc., of Aberdeen in Grays Harbor County. He is in large part responsible for the high quality of reclamation at several of the company’s sand and gravel pits. Mr. Stoken was nominated by Stephanie Zurenko, DNR Central Region Reclamation Inspector.
Mr. Stoken has been operating heavy equipment most of his adult life, and as a consequence of his grading skills and an outstanding “eye” for drainage and topography, he has made landforms that look natural from the otherwise linear features of the mines. At the Brooks (Fig. 9) and Sands mines in Grays Harbor County, Bummie has created wetlands that have sinuous shorelines and islands that will be beneficial and productive sites for waterfowl and other wildlife. The judges chose to recognize Mr. Stoken for his sense of what he can do to work with nature in mines.

**Individual Responsibility**

Mr. Stoken takes great care and pride in his reclamation efforts. His ability to imagine the landform and then create it is the reason why Northwest Rock chooses Bummie from among their many equipment operators to do reclamation work.

**References Cited**


The area surrounding Mount St. Helens has received much scientific attention since the eruption of 1980. The Washington State Department of Natural Resources (DNR) and the U.S. Geological Survey (USGS) are two major contributors to this research. In 1985, while employed with DNR’s Division of Geology and Earth Resources, I attended a field trip sponsored by the USGS to study the geology around Mount St. Helens and Mount Adams. During the trip, I recovered a slab of rock bearing many impressions made by vertebrates (Figs. 1, 2). On subsequent trips to the site, I collected more trackways, isolated footprints, and other ichnofossils (trace fossils).

Trace fossils from this region of Washington are worth studying for several reasons. The geology of the Miocene volcaniclastic rocks between Mount St. Helens and Mount Adams is complex, and few fossils have been found. These trace fossils and their abundance apparently indicate a varied vertebrate fauna. Vertebrate ichnofossils may give geologists who study these rocks better time and stratigraphic controls. Evidence of a well-established animal community may improve estimates of the deposition rates of these sediments through comparisons to the rates of animal repopulation in the area affected by the eruption of Mount St. Helens. At the very least, these traces of Miocene vertebrates may help fill gaps in our knowledge of paleontology and paleoecology in the western United States. This report is a preliminary attempt to identify the makers of the ichnofossils.

Almost all material was recovered from talus at the base of a 15-m-high cliff of volcaniclastic rock, composed of beds of fine- to coarse-grained, angular to subangular fragments of volcanic detritus. Weathered and altered pumice is a common component. The beds range from less than 1 to more than 30 cm in thickness and are well lithified. In some beds, there is a 3- to 10-fold change in thickness within a distance of less than 5 m. Cross bedding has not been observed. A thin bed of tuff(?) was recently discovered approximately 2 m above the trace fossil interval (Fig. 3). The entire sequence continues downslope (east) from the cliff. A rough measurement indicates that this sedimentary unit is more than 35 m thick. The rocks exposed along the fossil-bearing cliff are moderately folded but not overturned. Rocks downslope and to the north of the outcrop are not folded and dip less than 10 degrees. A creek divides more horizontal rocks on the north from the fossiliferous and folded sediments to the south and may indicate the presence of a fault. The fossil-bearing stratum can be traced for more than 10 m before it disappears under talus and vegetation.

R. C. Evarts and R. P. Ashley mapped the geology of the area that contains the track-bearing rocks (Evarts and Ashley, 1993; Evarts and others, 1987); they include the rocks in their widespread Tvs unit (“volcaniclastic sedimentary rocks of inferred epiclastic origin”). (See Walsh and others, 1987.) A radiometric age estimate of 22.6 ±0.6 Ma was obtained from a pyroxene andesite interbedded with these sediments about 4 to 5 km from the site. Evarts and Ashley further state that this date has been possibly reset by the Spirit Lake pluton and may be a minimum age. Therefore, it appears that the tracks were made by early Miocene animals (late Arikareean mammal stage).
Figure 2. Sketch and photo (facing page) of slab 1. The pitted area is the original impressed surface; the smooth area on the bottom of slab is the stratum bearing the subtraces. Note the discontinuity of craters on the top surface. Outlines of the carnivore(?) subtraces have been exaggerated to show the author’s interpretation of the footprint morphology. Arrows indicate the direction the trackway maker was traveling. Arrow in the photo with the degree measurement indicates the approximate declination of light from a 100-watt bulb relative to the slab surface; the bar is 10 cm long.
DESCRIPTION OF MATERIAL

Almost all examined ichnofossils were formed at the surface/air boundary (exogenic) and are molds. Rare isolated casts and counter slabs of rock have been found. This scarcity of natural casts is probably due to the fragility of the 5-mm layer of sediment that filled the impressions.

More than 75 percent of all the vertebrate impressions belong to fewer than ten trackways from which the gait and footprint size can be measured with reliability. Preservation of the footprints is good, although the larger carnivore-like traces are the least reliable for identification. Nonetheless, enough material is present to indicate the relative size of the animals, their gait, and the basic morphology of their feet.

All impressions can be grouped into five categories distinguished by shape and size—two are mammalian in origin, one is from a bird, and another may represent the markings made by a lizard-like animal. The fifth group was produced by water.

Impressions Made by Water

The slab in Figure 2 shows numerous round to subround impressions. They range from 0.3 to 1.3 cm in diameter and are 0.1 to 0.5 cm deep. There is an approximate alignment of similarly sized craters. The impressions were probably created by water falling from directly above the site or from splashed material (sediment and water) thrown up by passing animals. Falling water is suspected because of the random pattern of the impressions and the nearly circular outline. I considered impact by falling lithic detritus such as pumice, but foreign material has not been preserved in any impression. Splashed sediment and water thrown up by the activity of animals is a possible explanation, but I have found no supporting evidence.

Available material suggests that the impressions were produced by falling water. A raindrop origin appears to be unlikely because there is an uneven distribution of the impressions (Fig. 2). Raindrops can be expected to fall at random and to evenly cover a surface unless blocked by an obstruction. I have observed similar configurations elsewhere on other slabs representing the same stratum. A likely origin appears to be water falling from a branch of an overhanging tree or bush. Figure 4 shows the pattern made on fine beach sand from water falling off a deciduous shrub in late fall after a heavy fog; note the definite alignment of craters of similar size. Their size appears to be related to the diameter of the limbs on which the water droplets formed. Larger limbs and branches were observed to produce larger drops, smaller branches produced smaller drops. The complexity of the drip pattern on the beach surface is related to the complex intergrowth of the limbs of the shrub. This theory is made more plausible by the presence of fossil woody debris and leaf fossils in the talus. Plant remains tend to be poorly preserved, but I have found an outline of a sheathed bundle of (five?) pine needles.

Impressions Produced by Mammals

The majority of the trackways were made by mammals. Vertebrate classes such as the reptiles and amphibians were ruled out; the exception is the single trackway diagrammed in Figure 14. This classification is based on the measured pace angulation and footprint morphology.Digits of amphibians and reptiles tend to be of disproportionate length (Brown and others, 1984; Murie, 1974) and may be webbed with prominent claws. These characteristics are in contrast to the track producers, which were animals with an efficient style of locomotion. The limbs must have been placed well under the body, the straddle width was small (see Fig. 8), and the digits in all tracks are of similar size. Webbing is absent, and claw traces, where present, are small.

Pace angulation is a measure of locomotion efficiency and represents the placement of the legs and feet under the body during locomotion. The method for measuring this angle is dia-
grammed in Figure 5. This can be understood by comparing the placement of the limbs of a turtle and lizard with those of a dog. According to Peabody (1959), a turtle has a pace angle of about 65° and a lizard about 85°. These animals walk in a sprawled manner, with the limbs spread out from the body and the feet far from the midline of the trackway (Fig. 5). On the other hand, all fossil mammal trackways have pace angles greater than 150°. The pace angle of a modern dog is about 150°, reflecting the placement of the limbs and feet close to the midline of the trackway. There can be little argument that the dog walks in a more graceful and efficient manner than a lizard or turtle.

Figure 6 shows a scheme for connecting the ichnites (fossil tracks) to their probable mammalian creators. The distinguishing features for tentatively identifying the makers of the larger ichnites as carnivores are the apparent presence of digitigrady, inferred size of the track producer, and the number of digits in the manus (front feet) and pedes (hind feet), respectively. Digitigrady is a term used to refer to an animal’s ability to walk on its toes, or digits, like a cat, instead of on the sole of its foot, like a human or a bear (plantigrade). In the large ichnites, digitigrady is suggested by the impression of a plantar pad (the soft, triangular pad on the bottom of the cat’s or dog’s foot behind the digits) and the lack of a posterior metatarsal or metacarpal pad (the long and broad “sole” pattern of the human foot).

The smaller ichnites on the slab were likely made by rodents on the basis of the inferred size of the animal, its track size, stride length, and gait. Lagomorphs (rabbits and their relatives) were ruled out because of their large size and specialized hind feet. The only known Miocene insectivore families that could be candidates are the Erinaceidae (hedgehogs) and the Soricidae (shrews). The erinaceids probably can be excluded from consideration because of their large size and because modern representatives do not make the track patterns observed in the ichnites. The soricids are, in general, too small to have produced the stride and straddle lengths observed (Murie, 1974; Brown and others, 1984). Thus, the insectivores may be, with some confidence, excluded from consideration.

**Smaller (Rodent?) Mammal Tracks**

Tracks made by rodent-like animals make up the majority of the ichnites. I measured five exogenic trackways in which gait and descriptive measurements could be determined. I assume these trackways were formed by animals of similar build, perhaps members of the same taxon, on the basis of similarities in their construction. More than one individual may have been responsible for track creation, however.

Nearly all rodent-like trackways exhibit the gait pattern that Hildebrand (1974) defines as the half-bound. In this gait, either the right or left manus takes the lead and strikes the surface before the other three feet. The pedes appear to strike the ground in unison. This is common in present-day rodent locomotion. Trackway 1-1 shows a different gait pattern, called the bound, where hind- and forefeet strike the ground in unison, and there is no leading manus (Fig. 7). It is also a gait commonly observed in many types of small, fast-moving rodents.

The stride, measured from the extreme anterior of the left and right pedes, ranges from 8.5 (trackway 1-2) to 15.5 cm (trackway 1-1) (Fig. 2; refer to Fig. 8 for definitions). The average length is 11.7 cm. Stride length can vary by as much as 60 percent within the same trackway.

The intergroup distance corresponds to the length of extended flight (Gambaryan, 1974). It is the measure of distance that a saltating (jumping) animal is airborne, with all four feet simultaneously off the ground. An increase of this length corresponds to an increase in stride length and may show great variation within a trackway. In trackway 2-2 (Fig. 9), the variation between two consecutive measurements is nearly 51 percent (3.4 cm). The range of the intergroup distance is 7.0 to 12.3 cm.

Straddle width variation amounts to less than 0.2 cm (6 percent) in a single trackway. When all trackways are considered, the straddle width lies within a 3.2- to 3.8-cm range.

The five trackways are composed of 47 complete footprints—23 pedes and 24 manus. The length of the pes (hind foot) ranges from 1.0 (trackway 2-3) to 1.9 cm (trackway 1-1) and may vary within a single trackway by as much as 40 percent (trackway 2-2). The manus length ranges from 1.2 (trackways 2-2 and 1-3) to 1.8 cm (trackway 1-3). Variation in the length of the manus may be as much as 50 percent within a single trackway (1-3). This measurement is affected by the partial overlapping of adjacent footprints of different trackways. There is no apparent correlation between the length and width.
of manus or pes; the width does not get larger with an increase in the impression’s length. There is no evidence of backfilling of sediment from the track margins into the impressions, so this is not likely a reason for any discrepancy in the measurements.

Except for trackway 2-3, all pedes show distinct outward divarication (that is, they are directed away) from the main axis of motion. The left pes (eight measurements) divaricates 11°, and the right pes (four measurements) divaricates 8°. I saw no correlation between the amount of the divarication and the length of the stride or extended flight. The lack of a correlation may be due to the small number of measurements; a more accurate representation would be attained by a longer continuous trackway.

Many tracks have digit and claw impressions. Footprints in trackway 2-3 indicate that both right and left manus have five digits. A right pes in trackway 2-2 also has five digits. Individual casts of the rodent-like tracks that could not be matched to any trackway also indicate a similar phalangeal (toe or digit) count. Assuming that the animals that made these impressions were all of the same type, then the phalangeal formula of the animal was 5/5—five digits on both pedes and manus.

Differences in the widths of the straddle and the length of the pedes suggests that more than one individual was responsible for all the rodent-like impressions. The difference in length between the longest and shortest pes measurements of all examined footprints amounts to 0.9 cm, a discrepancy of 90 percent. Within any single trackway this discrepancy is less than 40 percent. Straddle variation is as much as 19 percent between the smallest and largest measurements (3.2 to 3.8 cm) when all the trackways are compared. The straddle variation is not more than 6 percent within any single trackway.

An animal’s body length can be estimated from the length of the pes impressions. Figure 10 is a graph of the pes length of modern-day rodents. Even with an allowance for error in measurements because of the nature of the sediment, the Miocene ichnites appear to have about 10.0 to 15.0 cm long, excluding the tail. This graph is not meant to imply any affinity of the track producers to recent animals but is simply to be used as a tool to determine body size. The important measurements are summarized in Figure 11.

### Large Mammal (Carnivore?) Tracks

The larger tracks are more questionable because their impressions are not as distinct as the others. Important features such as the digit and pad impressions are vaguely defined when viewed by direct, overhead light. Ridges separating these regions are subtle but can be seen in low-angled (to the slab) light. Also, these ridges can be easily traced by running the fingers over them. By these means, sufficient information was attained to determine the existence of a footpad (plantar), the style of gait, general size of the foot, and even the approximate size of the trackway producer. There is little doubt that the animals were digitigrade quadrupeds.

In Figure 12 (center trackway, 2-1), the record of motion begins with the impression of a right manus and is followed by seven more footprints; the last, a left pes, is incomplete. Each of the four feet is represented by two impressions. The footprints are grouped into pairs with the manus in front of the pes of the same side of the body. These groups are spaced about 8 cm apart.

On portions of footprints 2-1B and 2-1C (Figs. 5, 9), the topmost impressed surface is missing. Subtraces of approximately 1 cm depth are exposed in an apparently very fine grained, dark-gray sandstone. Between this sandstone and the upper layer, where present, small cavities have formed; this makes the top layer subject to breakage. The depth of the subtraces is evidence that the sediment below this surface was still wet when the tracks were formed.

Figure 5 gives track-measurement definitions for the larger footprints. Six measurements of stride length could be made on trackway 2-1. The range is 32.1 to 34.1 cm, and the average is
Eleven oblique pace measurements range from 15.7 to 18.4 cm, averaging 16.9 cm in length. Three separate track-breadth measurements fall within a range of 7.2 ±0.2 cm. The step length, as measured from the most posterior point of track 2-1A to a similar position on 2-1F, is 54.1 cm. The pace (step) angle was measured using six sets of points. This angle ranges from 152° to 165°, averaging 157°.

The two right manus impressions are 5.3 cm wide and 4.3 cm long. This compares well with the best preserved left manus (D), which is 5.2 cm wide and 4.4 cm long. The maximum length of all footprints, manus and pedes, corresponds to the long axis of what is presumed to be the fourth digit.

The two right pedes average 4.9 cm wide and 3.3 cm long. Left pedes are 4.4 cm wide and 3.3 cm long. This discrepancy between the length of right and left pedes is within the observed range of modern domestic carnivore (dog and cat) tracks.

The manus are impressed nearly twice as deeply as the pedes (5 mm compared to 2 to 3 mm, respectively), consistent with observations of many modern carnivores where the center of gravity is closer to the front limbs than to the hind limbs. More weight is placed on the front limbs, which results in a deeper impression. Both manus and pedes appear to have four depressions, which were probably made by four digits. This is a common phalangeal count in many living carnivores. No claw markings are visible on any of the digits, evidence that the carnivore-like track maker may have had retractable claws.

According to Casamiquela and others (1987) and Mossman and Sarjeant (1983), the gleno-acetabular distance is a measurement that gives the approximate trunk length of the animal (the length between the fore and hind limb attachments). This measurement is made from the distance between the midpoints of two consecutive pedes and manus impressions. Two measurements were made on trackway 2-1. The distance between the midpoint of manus D and F (most posterior part of the plantar pad) to the midpoint of pedes A and C is 21.7 cm. The other measurement between manus F/G and pedes C/E is 20.0 cm, but it may be in error due to the relatively poor condition of tracks G and H. If these measurements are valid, then the animal that produced these tracks would have been about the size of a house cat.

I observed gaits of living dogs and cats by dipping each of the animals’ paws into a different food coloring and having it move over a long sheet of paper and board (Fig. 12, the outside trackways). It became apparent that the ichnite-producer was most likely employing a leisurely walking gait at the time of the imprinting. This conclusion is supported by the works of Murie (1974) and Halfpenney and Biesiot (1986) on recent quadrupeds.

Figure 7. Comparison of selected rodent-like trackways drawn to the same scale. Arrow points in direction of movement. Letters refer to track designations in Figures 2 and 9. Gaits of all trackways (except 1-1) are what Hildebrand (1974) calls the half-bound. Footprints in trackways 1-1, 1-2, and 1-3 (solid outlines) occur on the original impressed surface. All footprints on slab 2 (2-2, 2-3) are subtraces.

Figure 8. Diagram showing methods for measuring rodent-like trackways (modified from Gambaryan, 1974). Large circles, pedes (hind feet); small circles, manus (forefeet); 1, width of base of pedes; 2, width of base of manus; 3, length of extended flight; 4, fore pace; 5, hind pace; 6, crossed flight; 7, stride length; 8, straddle width; 9, grouping length.
Figure 9. Photo and sketch of slab 2. (See Fig. 3 for its location on the talus pile.) Arrows indicate direction of movement of track producers. All footprints on the slab are subtraces. Figures 5 and 8 show the methods used for measuring the trackways in this study. Bar on photo is 10 cm long. Inset is a closeup of a right pes showing the 4 digit component of a carnivore footprint. Bar is 5 cm long. This footprint is not from slab 2. Arrows with degree measurements indicate the approximate declination of the incoming light from a 100-watt bulb relative to the slab surface.

Figure 10. Graph showing body length (excluding tail) ranges for extant North American rodent families when the pes (hind foot) length is known. Numbers in parentheses refer to the number of species per family considered. The relation of body length to pes length tends to be a linear plot by family group. The patterned area is the approximate plot of the trace fossils and is not meant to imply taxonomic affiliation. (Data from Hall, 1981.)
Bird Tracks

The best bird trackway is shown in Figure 13. The diagram is a composite of two counter slabs. Only the subtrace (cast) and the bottom of the mold is visible. The imprinted surface could not be observed without damage to the trackway. Other bird footprints, on other slabs, have been discovered but do not form any discernible trackway and could not be matched to those in Figure 13.

All impressions indicate an animal with three digits, presumably digits 2, 3, and 4. I saw no clear indication of digit 1, the hallux (“thumb”), in any footprint. Claw marks are intriguingly absent; most recent and fossil bird footprints show indentations made by claws (Brown and others, 1984). In contrast to many of the living non-wading birds, the digits in the trackway are relatively short and broad. The width may reflect what Brown and others (1984) call smooth, lobate, digital webbing found in living grebes (Wallace, 1955). It is possible that other types of webbed feet were responsible for the impressions. My observations of a domestic goose showed that indentations similar to the ichnites could also be produced by a distally webbed foot impressed into soft mud. The bird’s weight and the soft sediment substrate allowed the centers of the webbing to “bow up” between the digits, and a false “lobate” digit impression was formed. In many footprints the outline of this bowed-up webbing was not observed.

Only three well-preserved fossil footprints allowed reliable measurements. The digital length was measured from the rear of the imprint, in the approximate area of the metatarsal impression, to the tip of the digit. Only digit 3 showed a consistent length for all three tracks and ranged from 4.7 to 4.9 cm. The lengths of digit 2 ranged from 3.2 to 3.7 cm, and digit 4 varied from 3.4 to 4.4 cm. Divarication between digits 2 and 4 was very close in all tracks (106° to 109°).

Two measurements of stride and pace angulation measured from the most posterior point on the impression, show that pace angulation was 160° and 169° and stride length ranged from 18.6 to 19.4 cm.

It is possible to calculate the approximate height of the ichnite-producing bird to its hip joint (acetabulum) using trigonometry (Fig. 13 inset) if its step angle is known (Thulborn, 1989; Casamiquela and others, 1987). The step angle is formed between the lines drawn from the acetabulum (origin) along the legs to the feet (in a bipedal animal) when both feet are simultaneously placed on the ground while the animal is moving. Estimates of this measurement must be made on living animals that exhibit similar traits of footprint morphology, gait (walking), and ecology as the ichnite-maker. Using suitable photographs in Thompson and Ely (1989) and Udvardy (1977), I estimated the step angle to be from 27° to 35° for wading birds such as herons, gulls, and geese. From the formula given in Figure 13 and the average pace length of 9.7 cm for the ichnite-maker, the height could have been from 15.4 to 20.2 cm.

<table>
<thead>
<tr>
<th>TRACKWAY 1-1</th>
<th>TRACKWAY 1-2</th>
<th>TRACKWAY 1-3</th>
<th>TRACKWAY 2-1</th>
<th>TRACKWAY 2-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>gait style</td>
<td>bound</td>
<td>half bound</td>
<td>half bound</td>
<td>half bound</td>
</tr>
<tr>
<td>stride length (each cycle—pes to pes)</td>
<td>12.8 cm (15.6 cm)</td>
<td>8.7 cm (10.0 cm)</td>
<td>10.8 cm</td>
<td>10.4 cm (14.4 cm)</td>
</tr>
<tr>
<td>straddle (per grouping)</td>
<td>3.6 cm (C–D)</td>
<td>3.3 cm (C–D)</td>
<td>3.8 cm (C–D)</td>
<td>3.4 cm (C–D)</td>
</tr>
<tr>
<td>hind foot size (average) length/width</td>
<td>1.6 cm/0.8 cm</td>
<td>1.4 cm/0.8 cm</td>
<td>1.4 cm/0.9 cm</td>
<td>1.5 cm/1.0 cm</td>
</tr>
<tr>
<td>length of extended flight (intergroup)</td>
<td>11.0 cm (C–E)</td>
<td>7.0 cm (D–F)</td>
<td>7.8 cm (D–E)</td>
<td>8.2 cm (C–E)</td>
</tr>
<tr>
<td>diverticulation of hind foot from axis of motion</td>
<td>2 (C)</td>
<td>13 (D)</td>
<td>20 (C)</td>
<td>12 (C)</td>
</tr>
<tr>
<td>grouping length</td>
<td>4.4 cm (A–D)</td>
<td>3.8 cm (A–D)</td>
<td>4.3 cm (A–D)</td>
<td>6.2 cm (A–D)</td>
</tr>
</tbody>
</table>

Figure 11. Summary of measurements of the rodent trackways. (Refer to Figs. 2, 8, 9, and 11.)

Figure 12. Diagram comparing the gaits of domestic cats with fossil trackway 2-1 (center). Each cat was walking moderately fast, which is why the manus and pes are farther apart than is observed in the, possibly, slower walking ichnite-producer. RM, right manus; RP, right pes; LM, left manus; LP, left pes.
Probable Lizard or Salamander Impressions

The subtrace of a trackway of a small quadruped is diagramed in Figure 14. Individual footprints appear to be represented by groups of one to three indentations that were probably made by claws. Because this is a subtrace, it is impossible to be certain of the phalangeal formula for the trackway maker; even the differentiation between manus and pes is questionable. It is possible, however, to get some idea as to the gait, the efficiency of locomotion, size, and other criteria from the trackway measurements.

Six measurements of stride length ranged from 4.0 to 4.4 cm, with an average of 4.2 cm. Two pace measurements are 1.2 and 1.3 cm, respectively. The three reliable pace angulation measurements are 89°. A single interpes distance is 0.7 cm. The width of the pace angulation pattern is 1.7 cm.

According to Peabody (1959), the ratio of the stride length to the width of the pace angulation pattern is correlated with the pace angulation measurement for salamanders and other vertebrates. In the fossil trackway this ratio is approximately 2.5/1 and matches the expected pace angulation (about 90°) for animals with a salamander-like style of locomotion, body plan, and gait (slow walking). It therefore appears that the animal that created the footprints was likely built like a lizard or salamander. A “quick and dirty” but reliable estimate of the body length (distance between the attachments of the limbs to the trunk) was approximately 4.2 cm. More finds of these trace fossils will help refine these measurements and speculations.

CONCLUSIONS AND SPECULATIONS

From available evidence it appears that four types of vertebrates left impressions on a wet, muddy, surface in early Miocene time. The traces of what appear to be a wading bird, rodent-like animals, spatially associated large quadrupeds with carnivore affinities, and a probable lizard or salamander give tantalizing clues to an ancient ecology. The area, possibly a small lake or playa, was probably being visited by animals in search of food or drink. There is evidence of vegetation from the water drop impressions and twig and leaf fossils found in other strata. The existence of what are apparently small desiccation cracks in some of the ichnite-bearing rocks indicates that the body of water began to evaporate almost immediately after the animals’ visit.
Only a small part of the surface of the ichnofossil-bearing interval, perhaps less than 3 m², has been recovered. Almost every collected fragment of this surface bears some sort of trace fossil. Even with the available evidence it is apparent that a rich and fairly diverse animal community was thriving in this area around 23 million years ago. Volcanic eruptions and subsequent deposition of volcanic detritus were evidently sporadic enough to allow the formation or recovery of moderately complex animal communities. More work is needed on the sediments and taphonomy to better understand the environment represented by this thick rock unit.

No definite conclusions can be reached about the identity of the footprint makers, but there are many clues. Even with further trackway discoveries, classification will be tentative unless associated skeletal material is recovered.

Acknowledgments
I thank my mother, Flora Z. Kaler, for her help on nearly all of the numerous collecting trips to the site. W. A. S. Sarjeant, University of Saskatchewan, read an early draft of this study, supplied many excellent suggestions and comments, and introduced me to useful reference literature. Eric Schuster was a good source of information on specimen photography. Last, but not least, I thank my late pet goose, Brünnhilde, and her neighborhood canine and feline friends for helping me better understand vertebrate locomotion and footprint morphology.

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Radiocarbon Ages of Probable Coseismic Features from the Olympic Peninsula and Lake Sammamish, Washington

Robert L. Logan¹, Robert L. Schuster², Patrick T. Pringle¹, Timothy J. Walsh¹, and Stephen P. Palmer¹

¹Washington Department of Natural Resources
Division of Geology and Earth Resources
PO Box 47007, Olympia, WA 98504-7007

²U.S. Geological Survey
Box 25046, MS 966
Denver, CO 80225

During the past decade, we have searched for clues to the seismic history of western Washington. Our research has concentrated on sites on the Olympic Peninsula and in Lake Sammamish. Features we have examined include faults, submarine landslides, and landslide-dammed lakes. This article describes these investigations and discusses the implications of our radiocarbon ages.

Despite the considerable geographic separation of the Olympic Peninsula sites from Lake Sammamish, temporal relations of most sites we investigated are intriguing, and several may be closely related to other seismically induced features in the region (Atwater and Moore, 1992; Bucknam and others, 1992; Jacoby and others, 1992; Karlin and Abella, 1992; Schuster and others, 1992). A collapse of a portion of the Lake Sammamish shoreline near the Seattle fault, the Lake Crescent landslide complex in the northern Olympic Peninsula, numerous large rock avalanches in the southern peninsula that originated on rugged mountainsides composed of Crescent Formation basalt, and two young, nearby faults are natural features that can provide new insight and raise new questions about past seismic events in western Washington (Fig. 1).

In the interest of brevity and simplicity, we use the same terminology as in our article in the previous issue of Washington Geology (Pringle and others, 1998). We use Varnes’ (1978) classification of landslides, and we report uncorrected 14C ages. Both calibrated and uncalibrated ages are shown in Table 1. Years before present (yr B.P.) are years before 1950.

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Figure 1. Locations of radiocarbon-dated material and other selected neotectonic features in western Washington. CRF, Canyon River fault; SMEF, Saddle Mountain East fault. All dates in years B.P.
Table 1. Radiocarbon age data for selected landslide deposits in western Washington. * denotes influence of bomb 14C. Radiocarbon ages given in yr B.P.

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Beta Lab no.</th>
<th>14C age1 ±50</th>
<th>13C/12C adjusted age</th>
<th>Calibrated and corrected age (yr B.C. or A.D.)2 ±50</th>
<th>Legal location</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canyon River fault</td>
<td>109347</td>
<td>1880 ±70</td>
<td>-25.0</td>
<td>1880 ±70</td>
<td>sec. 19, T22N R6W</td>
<td>Detrital charcoal from silty sand layer that was either offset by fault or deposited shortly after last movement on the fault.</td>
</tr>
<tr>
<td>Lake Crescent (Harrigan Point)</td>
<td>96390</td>
<td>750 ±50</td>
<td>-25.1</td>
<td>750 ±50</td>
<td>sec. 14, T30N R9W</td>
<td>Wood from vertical snag at surface of lake. Unknowns include amount of outer surface erosion of the snag and if snag was rooted in lake bottom.</td>
</tr>
<tr>
<td>Lake Crescent (Thompson Point)</td>
<td>75774</td>
<td>300 ±60</td>
<td>-29.8</td>
<td>230 ±60</td>
<td>sec. 30, T30N R9W</td>
<td>Wood from branch of tilted (30° from vertical), rooted deciduous tree probably carried into the lake by a landslide; sampled at depth of 66 ft.</td>
</tr>
<tr>
<td>Lake Crescent (Saratoga Point)</td>
<td>39669</td>
<td>280 ±60</td>
<td></td>
<td></td>
<td>sec. 18, T30N R8W</td>
<td>Outer rings from rooted, tilted snag probably carried into the lake by a landslide. Amount of outer surface erosion unknown.</td>
</tr>
<tr>
<td>Hamma Hamma River</td>
<td>50545</td>
<td>2640 ±60</td>
<td>-22.4</td>
<td>2680 ±60</td>
<td>sec. 2, T24N R4W</td>
<td>Detrital branch-size wood that protruded into the water from the submerged portion of the lacustrine silts in the streambank at 4.4 ft below the river surface.</td>
</tr>
<tr>
<td>Hamma Hamma River (charcoal)</td>
<td>39798</td>
<td>2960 ±80</td>
<td></td>
<td>1401 B.C. (1158, 1145, 1134 B.C.) 921 B.C.</td>
<td>sec. 2, T24N R4W</td>
<td>Detrital charcoal from lake deposits slightly above boulders of landslide dam.</td>
</tr>
<tr>
<td>Lena Lake</td>
<td>32671</td>
<td>1340 ±50</td>
<td></td>
<td>634 B.C. (A.D. 671) 783 B.C.</td>
<td>sec. 35, T25N R4W</td>
<td>Wood from inner part of drowned snag taken at high-water stand. Amount of snag surface erosion unknown.</td>
</tr>
<tr>
<td>Lena Lake</td>
<td>58575</td>
<td>1470 ±60</td>
<td>-26.8</td>
<td>1440 ±60</td>
<td>sec. 35, T25N R4W</td>
<td>Wood from outer 15 rings of drowned snag sampled below the surface of lake-bottom silt.</td>
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<td>58576</td>
<td>1170 ±50</td>
<td>-25.8</td>
<td>1150 ±50</td>
<td>sec. 35, T25N R4W</td>
<td>Wood from outer rings that had grown over charred older wood of drowned snag.</td>
</tr>
<tr>
<td>Jefferson Lake</td>
<td>42123</td>
<td>1150 ±50</td>
<td></td>
<td>685 B.C. (A.D. 821, 840, 860) 967 B.C.</td>
<td>NE1/4 sec. 21, T24N R4W</td>
<td>Wood from inner part of drowned snag taken at high-water stand. Amount of snag surface erosion unknown.</td>
</tr>
<tr>
<td>Jefferson Lake</td>
<td>42124</td>
<td>1210 ±50</td>
<td></td>
<td>1678 B.C. (A.D. 1955) 1955*</td>
<td>NE1/4 sec. 21, T24N R4W</td>
<td>Wood from inner part of drowned snag taken at high-water stand. Amount of snag surface erosion unknown.</td>
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<tr>
<td>Jefferson Lake</td>
<td>58573</td>
<td>1080 ±60</td>
<td>-26.8</td>
<td>1050 ±60</td>
<td>NE1/4 sec. 21, T24N R4W</td>
<td>Outer rings adjacent to bark of drowned snag.</td>
</tr>
<tr>
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<td>58574</td>
<td>1080 ±50</td>
<td>-25.8</td>
<td>1070 ±50</td>
<td>NE1/4 sec. 21, T24N R4W</td>
<td>Outer rings adjacent to bark of drowned snag.</td>
</tr>
<tr>
<td>Price Lake</td>
<td>74570</td>
<td>1080 ±50</td>
<td>-27.0</td>
<td>1050 ±50</td>
<td>secs. 22 &amp; 23, T23N R4W</td>
<td>Wood adjacent to bark of snag that was drowned when the Saddle Mountain East fault scarp dammed Lilliwaup Creek.</td>
</tr>
<tr>
<td>Spider Lake</td>
<td>50550</td>
<td>1290 ±50</td>
<td></td>
<td>1260 ±50</td>
<td>sec. 10, T22N R6W</td>
<td>Wood from inner rings of eroded snag collected above the surface of the lake.</td>
</tr>
<tr>
<td>Spider Lake</td>
<td>50602</td>
<td>1190 ±60</td>
<td></td>
<td>1180 ±60</td>
<td>sec. 10, T22N R6W</td>
<td>Wood from inner rings of eroded snag collected above the surface of the lake.</td>
</tr>
<tr>
<td>Spider Lake</td>
<td>58580</td>
<td>1060 ±60</td>
<td>-25.5</td>
<td>1050 ±60</td>
<td>sec. 10, T22N R6W</td>
<td>Wood adjacent to the bark of drowned snag collected below surface of lake-bottom silt.</td>
</tr>
<tr>
<td>Spider Lake</td>
<td>58581</td>
<td>1160 ±50</td>
<td>-25.6</td>
<td>1150 ±50</td>
<td>sec. 10, T22N R6W</td>
<td>Wood adjacent to the bark of drowned snag collected below surface of lake-bottom silt.</td>
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<tr>
<td>Spider Lake</td>
<td>58582</td>
<td>1090 ±50</td>
<td>-24.4</td>
<td>1100 ±50</td>
<td>sec. 10, T22N R6W</td>
<td>Rings 73–87 in from bark, centered on ring 80. From root of Douglas-fir snag.</td>
</tr>
</tbody>
</table>
Lakes Crescent and Sutherland (Fig. 1) are located in a valley that was gouged out by the Juan de Fuca lobe of the continental ice sheet during the late Pleistocene. Steeply dipping, generally east-west striking, Tertiary sedimentary and volcanic rocks bound these lakes. The two lakes were formerly one large lake that drained eastward through Indian Creek and eventually the Elwha River, as Lake Sutherland does today. The lakes are now separated by a landslide complex that was emplaced during several catastrophic episodes of landslide activity from both sides of the valley (Reagan, 1909; Brown and others, 1960; Weaver, 1937; Fiksdal and Brunengo, 1980; Tabor, 1987; Logan and Schuster, 1991). The resulting rock-debris dam raised the surface of Lake Crescent above 80 ft, so that it now empties into the Lyre River, which drains northward into the Strait of Juan de Fuca.

The ages of emplacement of the landslide complex are difficult to determine with certainty. The landslide deposit of the Mount Storm King episode from the south valley wall, which is mentioned in local tribal legend (Reagan, 1909), is clearly older than debris originating from the north. It is not only geomorphically more subdued, but its toe underlies the landslide debris from the north valley wall. A count of the annual growth rings of a stump rooted on the youngest part of the slide complex indicates that the deposit is at least 600 years old. When the surface of Lake Crescent was raised to its present level, forested shoreline slopes should have been inundated, leaving an abundance of drowned trees to a depth of about 80 ft, unless the landslides occurred soon after the glaciers melted, before forests were established.

Using a glass-bottomed viewer to see to depths of nearly 100 ft, we searched the entire shoreline of Lake Crescent in an effort to find the drowned forest of submerged trees that theoretically should be rooted in the lake bottom. In several trips to the area, we have collected only four samples for \(^{14}C\) dating. Two of the samples are discussed in Logan and Schuster (1991). The other two samples were taken from a snag off Harrigan Point and from a submerged tree rooted at a depth of about 66 ft slightly east of Thompson Point near the western end of the lake (Fig. 1). The snag at Harrigan Point was sampled at the surface of the lake from a boat and had almost certainly been eroded by wave action and decay. Although we do not know how much erosion has taken place, previous experience (Logan and Walsh, 1995; Pringle and others, 1998) has shown that loss of 200 to 300 years (or several inches) of outer wood is not uncommon. This snag yielded a corrected \(^{14}C\) date of 750 ±50 yr B.P. (Table 1). Allowing for erosion, the tree would be about 600 years old (or younger). This age is similar to the minimum age of the landslide complex as indicated by the age of the rooted stump mentioned above. The snag is a conifer and appeared to be vertical, as if in growth position. This would suggest that it was drowned by an abrupt rise in the level of Lake Crescent. However, because we sampled it from the surface without help from a diver, we do not know if the

<table>
<thead>
<tr>
<th>Sample location</th>
<th>Beta Lab no.</th>
<th>(^{14}C) age (^{13}C/(^{12}C)</th>
<th>(^{13}C) adjusted age</th>
<th>Calibrated and corrected age (yr B.C. or A.D.) (^1)</th>
<th>Legal location</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Dry Bed Lake</td>
<td>50544</td>
<td>1160 ±50</td>
<td>-23.9</td>
<td>1180 ±50</td>
<td>S1/2 sec. 12, T21N R6W</td>
<td>Wood from inner part of eroded snag, broken from top of snag during high-water stand.</td>
</tr>
<tr>
<td>Lower Dry Bed Lake</td>
<td>58570</td>
<td>930 ±50</td>
<td>-26.2</td>
<td>920 ±50</td>
<td>S1/2 sec. 12, T21N R6W</td>
<td>Rings 68–92 in from bark centered on ring 80. From stem of Douglas-fir snag.</td>
</tr>
<tr>
<td>Lower Dry Bed Lake</td>
<td>58571</td>
<td>1010 ±50</td>
<td>-24.3</td>
<td>1020 ±50</td>
<td>S1/2 sec. 12, T21N R6W</td>
<td>Rings 68–92 in from bark centered on ring 80. From stem of Douglas-fir snag (same tree as above).</td>
</tr>
<tr>
<td>Lower Dry Bed Lake</td>
<td>58572</td>
<td>1030 ±50</td>
<td>-26.1</td>
<td>1010 ±50</td>
<td>S1/2 sec. 12, T21N R6W</td>
<td>Rings 72–86 in from bark, centered on ring 80. From root of Douglas-fir snag.</td>
</tr>
<tr>
<td>Campbell Tree Grove Campground</td>
<td>50538</td>
<td>710 ±60</td>
<td>-25.3</td>
<td>710 ±60</td>
<td>sec. 15, T23N R8W</td>
<td>Small 3/8 in. diameter twig-size pieces of wood recovered from drill hole at 16 ft below the ground surface, significance of date questionable.</td>
</tr>
<tr>
<td>Lake Cushman</td>
<td>50539</td>
<td>360 ±50</td>
<td>-22.5</td>
<td>400 ±50</td>
<td>sec. 10, T23N R5W</td>
<td>Wood adjacent to the bark of a vertical snag buried by landslide debris.</td>
</tr>
<tr>
<td>Lake Cushman</td>
<td>50540</td>
<td>390 ±50</td>
<td>-23.1</td>
<td>420 ±50</td>
<td>sec. 10, T23N R5W</td>
<td>Wood from adjacent to the bark of a vertical snag buried by landslide debris.</td>
</tr>
<tr>
<td>Lake Sammamish (Greenwood Point)</td>
<td>80713</td>
<td>1450 ±40</td>
<td></td>
<td>1430 ±40</td>
<td>sec. 18, T24N R6E</td>
<td>Sample of inner wood from the top of a snag protruding from the lake surface.</td>
</tr>
<tr>
<td>Lake Sammamish (Greenwood Point)</td>
<td>80917</td>
<td>1330 ±50</td>
<td></td>
<td>1320 ±50</td>
<td>sec. 18, T24N R6E</td>
<td>Sample of inner wood from the top of a snag protruding from the lake surface.</td>
</tr>
<tr>
<td>Lake Sammamish (Greenwood Point)</td>
<td>117413</td>
<td>1050 ±60</td>
<td>-28.4</td>
<td>1000 ±60</td>
<td>sec. 18, T24N R6E</td>
<td>Sample of upper part of root, 15 rings in from bark of a drowned tree that was rooted in a landslide deposit on the bottom of the lake.</td>
</tr>
</tbody>
</table>

\(^1\) Radiocarbon ages are normalized to \(^{13}C = -25.0\%o\) unless no value is shown in column 4. Error terms are \(1\sigma\) with a lab error multiplier of 2 unless noted.

\(^2\) Radiocarbon ages are calibrated in sidereal (calendar) years using tree ring data in the CALIB 3.0.3 program of Stuiver and Reimer (1993) and reported as \([-1\sigma, (calculated intercept age), +1\sigma]\) using a lab error multiplier of 2. Commonly, fluctuations in the calibration curve may yield more than one intercept or calibrated age. B.P. (before present) ages are reported with respect to A.D. 1950. Where shown in brackets, a correction factor was applied to adjust lab data for approximate number of growth rings of the sample from the bark. See Colman and others (1987), for a discussion of \(^{14}C\) terminologies.
tree is rooted. We are left with the question—Why aren’t there more submerged trees in Lake Crescent?

A photograph (Fig. 2) taken by a diver at a depth of 60 to 80 ft in Lake Crescent about 4.5 mi east of Fairholm (Fig. 1) depicts a tree in apparent growth position. We hired another diver to sample the tree, but he was unable to find it or any other drowned trees along a 300-ft section of the shoreline in that area. However, he did report seeing an apparent ancient shoreline or beach at about 80 ft below the lake surface.

Farther west, at the site near Thompson Point (Fig. 1), a diver from the National Park Service (NPS) recovered a sample from a drowned deciduous snag. The snag was rooted but was tilted about 30° from vertical. We could not determine from its orientation if the tree was in its original growth position. Furthermore, the morphology of the hillside above the adjacent shoreline strongly suggests that the submerged tree rode a landslide to its present location. The sample yielded a 14C age of 300 ±60 yr B.P., supporting the likelihood of landslide emplacement after Lake Crescent rose to its current level at least 600 years ago. The age is close to the 280 ±60 yr B.P. age (from an eroded snag; Logan and Schuster, 1991; also Table 1) from Saratoga Point. Could it be that both landslides were caused by an earthquake at about that time?

Despite being stymied by the lack of drowned trees and other evidence, such as organic deposits in depressions on the surface of the landslide complex that separates the two lakes, we are continuing our efforts to determine the age of the landslide that raised Lake Crescent to its present level. We believe that such a determination is important to understanding the seismic history of western Washington. Our next step may be to core sediment in the bottom of Lake Crescent for stratigraphic or radiocarbon evidence.

**Hamma Hamma River**

The Hamma Hamma River flows from the east flank of the Olympic Range into Hood Canal in the Puget Lowland (Fig. 1). At its confluence with Cabin Creek, the river was dammed by a large rock avalanche that originated in the basalt cliffs above the south bank. Fine lake sediment containing organic material filled the valley bottom upstream of the landslide dam, forming the large flat area on which the Lena Creek Campground was built. We have obtained five radiocarbon dates from wood and detrital charcoal in these sediments. The samples yielded radiocarbon ages of about 2,900 yr B.P. (Table 1) and younger.

The wood samples were taken from the submerged portion of a cut bank at depths ranging from 4.4 to 6.8 ft below the river’s surface (Fig. 3). By using a long-handled tree pruning device, we were able to reach down into the river to saw off and recover wood from small-diameter logs and branches that protruded from the submerged bank into the water. The oldest wood was taken 6.8 ft below the surface of the river at the base of the landslide. A photograph (Fig. 3) taken by a diver in the Hamma Hamma River shows detrital wood exposed in the submerged part of a stream bank in the Hamma Hamma River. Radiocarbon dating of the wood from this and a nearby site established a minimum age of about 2,900 yr B.P. for the sediment deposited upstream of the landslide that dammed the river.
of the exposure (Fig. 3). With one exception (see Table 1), the upper samples are generally younger than the lower samples. This exception can be attributed to the chaotic nature of deposition of wood and sediment in the aggrading shallow lake bottom or to the expected standard deviations in radiocarbon ages. Because the total depth of sediment impounded by the Hamma Hamma River rock avalanche is unknown, the 2,900 yr B.P. date represents only a minimum age for the slide. A similar estimate of the minimum age of the landslide is provided by another radiocarbon date of 2,960 ±80 yr B.P. from detrital charcoal in silt slightly above basalt boulders that make up the landslide deposit.

The dam that impounded the sediments in the Hamma Hamma River valley must have been breached between about 2,500 and 600 years ago. About 4 ft of sediment was deposited during the 400 or so years for which we have some age control. The top of the impounded sediment is at least 10 ft above the surface of the river at the sample location, so considerably more sedimentation took place after the youngest (2,500 yr B.P.) wood was deposited. If we assume that the sedimentation rate behind the dam was on the average about 1 ft per 100 years, it is possible that the dam could have been breached at about 1,000 to 1,500 yr B.P.

Dendrochronologic observations suggest that the youngest sediment behind the landslide dam is at least 600 years old. We estimated this age from annual growth rings on the stump of a cedar that had grown on the impounded sediments. (We counted 429 rings on the outer part of the hollow tree and estimated the number of missing rings to be 100 to 200.) Could the landslide dam have been breached during an extremely large earthquake at about 1,100 years ago, about the same time as the other landslide dammed lakes formed nearby?

### Lena Lake

Located only 2 mi northwest of the Hamma Hamma River rock avalanche (Fig. 1), Lena Lake is also impounded by a rock avalanche, this one derived from a basalt ridge slightly east of the lake. Interpretation of the ages of wood retrieved from snags in Lena Lake is complicated by the fact that the surfaces of most of the snags consist of charred wood, indicating that a fire swept the area at one time. The fire may have killed some trees and charred others without killing them before the lake formed. New growth over fire-blackened wood on sample Beta 58576 supports this interpretation. Sample Beta 58575, for example, was composed of the first 15 rings adjacent to bark and was sampled below the lake bottom surface. Its age of 1,470 ±60 yr B.P. (probable date of the fire) is anomalously older than Beta 58576 (1,170 ±50 yr B.P.), which is also outer wood taken slightly below the surface of the lake-bottom mud from outer wood that had grown over a fire scar. Beta 58575 is also older than two other samples of wood closer to the center of the snag; these were taken at higher water stand, above the lake bottom probably from an eroded surface, and yielded uncorrected ages of 1,340 and 1,300 ±50 yr B.P. We infer that the 1,170 ±50 age is closest to the actual age of the landslide that impounded the lake.

### Jefferson Lake

Situated about 3.5 mi southwest of the Hamma Hamma River site, Jefferson Lake is studded with drowned conifer snags in vertical growth position. Two sets of two radiocarbon ages from Jefferson Lake are listed in Table 1. The first two ages are not corrected for ¹³C, and the samples were taken during reconnaissance stages when the water level of the lake was relatively high. We cut the samples from the upper, eroded parts of snags. From these samples we expected and got older ages (1,150 ±50 and 1,210 ±50 yr B.P.). Subsequent samples, taken during a much lower stand of the lake, were of wood adjacent to the bark on preserved stump roots and yielded ages of 1,080 ±50 to 60 yr B.P. These probably closely represent the age of the Jefferson Lake landslide dam. The upper part of Jefferson Lake is separated from Jefferson Lake by an alluvial fan and small landslide and does not contain snags. We suspect that if any snags existed, they have been buried by sediments.

### Pine Lake

Pine Lake (Figs. 1, 4) is located in the headwaters of Pine Creek, a tributary of the Skokomish River. It is about 4 mi east of the Wynoochee Reservoir, 2.5 mi northwest of Spider Lake (Schuster and others, 1992), and 3 mi north of the Canyon River fault (Walsh and others, 1997). Pine Creek is dammed by large, locally derived, angular basalt boulders similar to those that dammed the Hamma Hamma River and other landslide-dammed lakes in the southeastern Olympics. The boulders originated from a bowl-shaped depression in the ridge that bounds the north side of the lake. The antiquity of the landslide is confirmed only by the conifer trees growing on both the landslide deposit and the landslide scarp. Cores from one of these trees yielded a minimum of 541 annual growth rings. The age of the stand of old-growth trees in the general vicinity of the lake is 690 years, on the basis of the last known local wildfire (Richard Carlson, U.S. Forest Service [USFS], oral commun., 1998). The lack of an ancient drowned forest in the lake could be due to the lake’s small size and rapid sedimentation rate. A delta of fine sediment occupies a portion of the upstream part of the lake. Also, large pulses of sediment could have been

![Figure 4](image)
delivered to the lake through several steep ravines that feed into the lake. In aerial photographs, these ravines appear as openings in the tree canopy and are likely channels for debris torrents. It is also possible that the landslide that impounds Pine Lake could have completely buried the forest that presumably covered the ancient valley floor.

**Spider Lake**

A drainage divide between the Skokomish and Satsop River basins was moved westward about one mile when the large rock avalanche that currently impounds Spider Lake thundered into the headwaters of the middle fork of the Satsop River. Spider Lake now drains eastward into Cedar Creek, a tributary of the Skokomish River. The lake contains an abundance of snags in growth position that are easily reached when the water level is low (Fig. 5). Previously reported radiocarbon ages of $1,290 \pm 50$ and $1,190 \pm 60$ yr B.P. (Schuster and others, 1992) were from samples obtained during a high-water stand and from inner rings of snags. Again, as expected, our later samples, taken from outer wood adjacent to bark during a lower water stand, resulted in three younger ages: $1,060 \pm 60$; $1,090 \pm 50$; and $1,160 \pm 50$ yr B.P., similar to ages from other nearby faults and landslide-dammed lakes.

**Dry Bed Lakes**

“Lower” (LDBL) (Fig. 6) and “upper” Dry Bed Lakes (UDBL) (Fig. 7), located about 6.5 mi south-southeast of Spider Lake (Fig. 1), are separated by a large landslide deposit that is probably much younger than the landslide that impounds LDBL. The age of LDBL is well established at about 1,100 yr B.P. as suggested by radiocarbon ages for outer wood beneath the bark of drowned trees in LDBL (Table 1) and those ages previously reported by Schuster and others (1992). There are no drowned trees in UDBL; however, cores from a living hemlock and a Douglas fir on the upper landslide divide each contained about 200 rings and provide a minimum age for the slide. Average recurrence for wildfires in the southern Olympic Peninsula is about 200 years (Richard Carlson, USFS, oral commun., 1998), so the slide could be much older than 200 years, or possibly the same age as the Lake Cushman (Table 1) and Lake Crescent landslides.

**Campbell Tree Grove Campground**

Located near the headwaters of the West Fork Humptulips River, the Campbell Tree Grove Campground is situated in a valley carved by an alpine glacier. Sometime after the glacier retreated, large pieces of rock debris slid or fell from the ridge on the north side of the valley. In an unpublished 1978 hydrogeologic project report for a water well for the campground, USFS personnel identified the rock debris as a landslide deposit.

During the drilling of the well through the rock debris into underlying alluvium, the drill penetrated wood at 16 ft below the surface. USFS geologists suggested that the wood was probably part of a tree that was killed and buried by the rock debris. Radiocarbon analysis of the sample resulted in an uncalibrated $^{14}$C age of $710 \pm 60$ yr B.P. (Table 1).

Estimating the age of the slide from this sample, however, is problematic. First, we do not know what part of the tree the wood is from, so a radiocarbon date would be a poor estimate...
of the age of burial. The sample appears to be the remains of small limbs about \( \frac{3}{8} \) in. in diameter, which suggests that the wood could be from young parts of a tree, and therefore give a more accurate estimate of age of death and burial.

Second, after we had received the radiocarbon date, we determined that the rock debris in the campground area probably has accumulated periodically by relatively small episodes of rockfall, not as one large rockslide. Unlike the other rockslide sites, this one lacks a large bowl-shaped source area on the upland slopes and is, instead, situated below a narrow, steep-sided ravine that appears more likely to occasionally calve blocks of rock. The oldest trees on the surface of the landslide deposit (Fig. 8) are as much as 7.5 ft in diameter and are about 450 years old (determined by counting rings on recently cut Douglas fir stumps). Several other populations of younger trees also grow on the rock debris. Many of the larger trees have large boulders leaning against them and could have survived occasional rockfalls but not a major rockslide. Openings in the canopy created by large rocks crashing through the forest would allow growth of the smaller trees. Windstorms or wildfires could also cause canopy openings, but evidence for such events tends to be short lived.

**Lake Cushman**

A large rockslide from Mount Rose, above the north shore of Lake Cushman, buried a rooted tree from which we were able to sample wood (Fig. 9). The samples were taken from wood adjacent to the bark, and thus represent the youngest wood in the tree. We do not know if the tree was alive when it was buried; that is, the sample may have come from a snag that had been dead for more than 100 years. It follows that our approximately 400 yr B.P. age (Table 1) from the snag could be older than the actual age of burial by the landslide. Therefore, the landslide may have occurred as recently as 300 yr B.P., possibly about the same time as the upper of the Dry Bed Lakes formed or landslides were activated at Lake Crescent.

**Price Lake**

Two active shallow crustal faults have been identified in the southeast Olympic Mountains. The Saddle Mountain East fault (SMEF) has produced a scarp that dams Lilliwaup Creek to form Price Lake (Fig. 1) (Carson, 1973; Wilson, 1975) located 2 mi east of Lake Cushman. We obtained a sample from the outer wood of a snag that was rooted in the bottom of the lake. The tree from which the wood sample came must have died by drowning within the year (Dan Omdal, Washington Department of Natural Resources [DNR], oral commun., 1998) following the latest seismic episode on the SMEF. The sample
(Beta 74570) yielded a radiocarbon age of 1,050 ±50 yr B.P., similar to several of the landslide ages reported in Table 1.

The Canyon River fault (CRF, Fig. 1) is the other local active fault. This fault also formed a scarp that dammed local drainages. Walsh and others (1997) reported an age of 1,880 ±70 yr B.P. from detrital charcoal that probably represents a maximum age for the latest movement on the fault.

On the basis of their ages and location, these young structures could be the source for moderate earthquakes responsible for formation of the nearby landslide lakes. However, they are also similar in age to other seismically suspect features in western Washington (Fig. 1).

**Lake Sammamish**

Greenwood Point is located at the southern end of Lake Sammamish less than a mile south of the projected trace of the Seattle fault (Bucknam and others, 1992) and associated nearby structures (Fig. 10). Two embayments along the north shoreline of the point, clusters of tilted tree snags offshore, and depth-finder sonar profiles of the lake bottom provided evidence that the shoreline collapsed and slid into the lake, carrying an ancient forest with it. If a great earthquake occurred about 1,100 years ago, as suggested by other studies referenced above, then it is reasonable to speculate that the shoreline could have collapsed as part of a seismically induced landslide.

Logan and Walsh (1995) reported radiocarbon ages of 1,450 ±40 and 1,330 ±50 yr B.P. (Beta 80713 and 80917, respectively, in Table 1) for wood recovered from snags that protrude from the surface of Lake Sammamish near Greenwood Point. The ages are probably about 200 years too old because they came from the inner (older) parts of the trees (Logan and Walsh, 1995). In a cooperative effort with Gordon Jacoby of Lamont-Doherty Earth Observatory, Columbia University, we employed divers to recover wood from trees that were rooted on the surface of the submarine landslide. Radiocarbon analysis revealed that one of the trees rooted in the landslide surface drowned about 1,050 ±60 years ago (Table 1). The sample was from a root of the tree about 15 rings from the bark, and the radiocarbon age should be very close to the time of the tree’s death.

**Discussion**

To date, we have found evidence of fault activity or possible seismically induced landsliding in three general age clusters: about 2,900, 1,100, and 300 yr B.P. The ages apparently fit the timing of other seismic or tectonic features that have been identified in the Puget Lowland (see, for example, Fig. 1) and subsided marshes along Pacific Ocean coastline (Atwater, 1996). However, our data lack the resolution to distinguish between locally induced or regionally induced features.

In one sense, the most common and most tightly spatially related radiocarbon ages cluster around 1,100 yr B.P. in the southeast Olympic Range. Does this mean that the large rock avalanches found there were caused by shallow nearby earthquakes that occurred on the Canyon River fault and (or) the Saddle Mountain East fault? On the other hand, 1,100 yr B.P. matches the timing of movement on the Seattle fault and Pacific coast tidal marsh subsidence linked to a large subduction zone earthquake.

Although the evidence permits the 300 yr B.P. features to be correlated to the A.D. 1700 event (Atwater, 1996; Atwater and Hemphill-Haley, 1997; Yamaguchi and others, 1997; Jacoby and others, 1997), the events are not well enough constrained in time or space to demonstrate that they had a single cause.
Another possibility is that they were local events closely spaced in time.

The 2,900 yr B.P. age on the Hamma Hamma River site is within the 2,800 to 3,300 yr B.P. range of Atwater’s (1996) tidal marsh subsidence event. Perhaps the Hamma Hamma River landslide was triggered by a subduction zone earthquake, too.

Acknowledgments

We thank Ken Neal (retired), Peter Erban, and Dennis Schneider of the USFS for providing information on the Campbell Tree Grove Campground area; Richard Carlson (USFS) for providing forest history information; Brian Atwater and Fitzhugh Lee (retired) of the USGS for field advice, and Boyd Benson for help in retrieving samples; Doug Williams, Mike Chevalier, Ken Dean, and Craig Mason of DNR Aquatic Resources Division for retrieving wood from Lake Sammamish and searching Lake Crescent for submerged trees; Rick and Terry Manning for information about Lake Crescent; Gordon Jacoby of Lamont-Doherty Earth Observatory of Columbia University for funding retrieval of wood from Lake Sammamish; Mike Butler, Larry Lang, and the NPS dive team for the search for and recovery of wood from Lake Crescent; Cathrine Kenner DNR Division of Geology and Earth Resources (DGER) and Leslie Pringle for their assistance in our dendrochronology research; and Eric Schuster (DGER) for his technical review.

References Cited


Mt. Rainier’s Deadly Potential

In 1997, Oregon Public Broadcasting released this half-hour video on the geologic hazards associated with Mount Rainier, primarily lahars, mudflows, and debris flows, but not excluding an eruption. You can order this film ($25) from Oregon Public Broadcasting, 7140 SW Macadam, Portland, OR 97219, or by calling (503) 293-1982. Please specify Oregon Field Guide episode #909 and the film title. (The film contains footage of Division geologist Pat Pringle at work.) Oregon Public Broadcasting has a web page: http://education.opb.org/learning/ofg/rainier/order.html.


Notes on the new Washington State fossil, *Mammuthus columbi*

Bax R. Barton

Box 278

Seahurst, WA 98062-0278

The appearance of a note regarding the new Washington State fossil species in *Washington Geology* (v. 26, no. 1, 1998) leads me to offer some additional observations concerning this species and its discovery in Washington.

Unlike mastodons, which were not elephants, mammoths (genus *Mammuthus*) were large, specialized elephants common to the Pleistocene epoch. This genus first evolved in the early Pliocene (4.0 to 5.0 Ma) of Africa, and by the early Pleistocene (ca. 1.7 Ma), mammoths had spread throughout Asia and into North America (Shoshani and Tassy, 1996; Webb and others, 1989).

The Columbian mammoth was first recognized as a distinct species by H. Falconer in 1857 from subfossil specimens recovered near Darien, Georgia, and housed in the collections of the British Museum of Natural History. Falconer argued that these new finds from North America were morphologically distinct from the two previously known species of mammoth (*M. meridionalis*, the “southern mammoth”, and *M. primigenius*, the “woolly mammoth”) and constituted a new species, which he named *Elephas* [*M.*] *columbi*. Since then, there have been a great many more finds of Falconer’s ‘new’ mammoth, including many from Washington State. We know much more about this species than Falconer could learn from the few specimens available to him at the time (Falconer, 1857).

Because of their noteworthy size and taphonomic rigor, mammoth remains (mostly molars) are probably the most commonly reported vertebrate subfossils in this state. Of the two species of mammoth found in Washington—*M. imperator* and *M. columbi*—Columbian mammoths are by far the most common. Many finds from this state have previously been referred to as woolly mammoths, but thus far none has been substantiated as *M. primigenius* when analyzed by modern methods. In the Puget Lowland, of 31 previously reported finds that could be analyzed to the species level, 27 (or 87 percent) proved to be from Columbian mammoths (Barton, 1992).

In western Washington, mammoth finds are heavily concentrated in the central and northern Puget Lowland, though a few are reported from the outer Pacific coastal zone and from the lower Columbia River subprovince. The earliest mammoth finds recovered from western Washington were discovered at Scatchet Head on Whidbey Island around 1860 (Lawson, 1874), but these are thought to have been destroyed in the San Francisco earthquake and firestorm of 1906 before they could be satisfactorily referred to species. Another specimen from the same locality, apparently recovered some time in the 1880s, is currently part of the University of California, Berkeley, paleontological collections, and this specimen is clearly from a Columbian mammoth.

In eastern Washington, virtually all of the mammoth finds are from the Columbian Basin. Here the earliest find of a Columbian mammoth may be that of a partial mandible (jaw) and molar recovered along the Walla Walla River in 1870 and now part of the collections of the University of Oregon. Other early mammoth finds were made on the Copelin Ranch along Hangman Creek, Spokane County, in 1876. These finds, later identified as from *M. columbi*, were reportedly shipped to New York and Chicago, where they became part of the Cope Collection of the American Museum of Natural History and the Chicago Academy of Science Collections in the Field Museum of Natural History (Hay, 1927).

What little we know of the diet of mammoths in general and Columbian mammoths in particular is derived from three sources. As mammoths were elephants, it is assumed that the dietary preferences of the two remaining genera of elephants, *Elephas* and *Loxodonta*, give some indication of the diet of mammoths (Eltringham, 1982). Secondly, our Russian colleagues have analyzed the pollen and spore contents of the gastrointestinal tracts from several of the frozen *M. primigenius* carcasses from Siberia (Ukraintseva, 1993). Finally, pollen and initial (presence/absence only) macrobotanic analysis has been carried out on desiccated dung boluses recovered from some of the dry caves of the Colorado Plateau—boluses most likely from Columbian mammoths (Hansen, 1980). All of these analyses suggest that mammoths were obligate herbivores with a dietary preference for graminoids (grasses and sedges), *Artemisia* and chenopods (herbs), and meadow-bog mosses, ferns, and aquatic plants. In some instances, these data suggest a diet of as much as 95 percent grasses and sedges.

Evidence for the presence of pine (either cones or needles) in their diet is minimal, and it is unlikely that pine ever constituted more than 1 percent of a Columbia mammoth’s chosen diet. At such low levels of consumption, it is more likely that any pine in their diet was accidentally ingested while they foraged for grasses and sedges across meadows and around the edges of bogs and ponds.

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ERRATA FROM THE PREVIOUS ISSUE

We had a major typesetting error in the article “New radiocarbon ages of major landslides in the Cascade Range, Washington” in Washington Geology, v. 26, no. 1, p. 32. Part of the page should be replaced. Simply copy this page and cut along the dashed line. Paste this over the text on p. 32 and all will be well.

When citing the article in a list of references, please cite as follows:


Age estimates that have been derived from radiocarbon \(^{14}C\) dating methods are given as “yr B.P.,” meaning radiocarbon years before present, where the “present” is A.D. 1950. Radiocarbon years can differ slightly from calendar years because of variations in the carbon-isotope content of atmospheric carbon dioxide through time. For simplicity, raw radiocarbon ages are used in this text. Table 1 on p. 34 shows both raw ages and calibrated ages.

Previous researchers have suggested that rock slide and debris-avalanche deposits record prehistoric seismic shaking in Washington (Schuster and others, 1992, 1994, 1995; Engbretson and others, 1995, 1996), neighboring British Columbia (Clague and Shilts, 1993; Evans and Savinyy, 1994), and elsewhere (Keefer, 1984). The landslides mentioned herein were likely to have been triggered by strong shaking for reasons similar to those noted by Schuster and others (1992) in their study of rock avalanches in the eastern Olympic Mountains:

- The rocks that slid or avalanched have not failed at such scales historically during storms.
- Worldwide, 29 of 71 rock avalanches that are included in an inventory of landslide dams (Costa and Schuster, 1991) were triggered by earthquakes having magnitudes of 6.0 or greater (Keefer, 1984).
- In New Zealand, the distribution of lakes dammed by landslides approximates the locations of shallow earthquakes of magnitude 6.5 or greater (Perrin and Hancock, 1992).

Evidence of these earthquakes can be preserved when the landslides bury forests and (or) create natural dams that cause a lake to form and thereby a forest to drown. The lakes and landslide deposits commonly provide a fairly anoxic environment that drastically slows the rate of decomposition of drowned or buried snags (dead trees), including Douglas fir and western hemlock, which are susceptible to relatively rapid deterioration in air (Cline and others, 1980; Harmon and others, 1986; Fig. 2). By studying and radiocarbon dating the remains of plants, such as rooted trees that are preserved in the lakes (subfossil trees), we can estimate the age of the landslide and of its possible triggering earthquake.

At five of the sites mentioned in the introduction, landslide-dammed lakes that were impounded at the time of the landslide are still in existence. The drowned forests preserved in these lakes, the snags or carbon preserved in deposits at the other locations, and the landslide deposits are the subject of this paper.

During the study, we also visited Tomyhoi Lake, a landslide-dammed lake in the North Cascades (T40N, R5E); landslides along the Cascade River at Kindy Creek (T34N, R12E), at Newaukum Lake (T14N, R3E), and at Hager Lake (T13N, R9E). In addition we visited three landslides along the upper Cispus River: west of Blue Lake (T11N, R9E) and at Johnson Creek and Wobbly Lake (both T11N, R10E). We could not find subfossil trees or other organic material suitable for dating at any of these sites. A carbon sample found beneath

Earth Science Week Set for October

“The goal for Earth Science Week,” says American Geological Institute (AGI) President Susan Landon, “is to have every geoscientist in the country do something in his or her community to promote the earth sciences.” As sponsor of Earth Science Week, AGI is a clearinghouse for ideas, activities, and special events, and provides support materials that make it easy for volunteers to participate. Schools, universities, museums, state geological surveys, and AGI member societies are planning Earth Science Week events.

The governors of 14 states have issued Earth Science Week proclamations, and more are expected. The foundation of each proclamation is that geology and the earth sciences are fundamental to society and to our quality of life. Citizens who understand geology and the earth sciences can make wise decisions for land use and management. The earth sciences are crucial for addressing environmental and ecological issues and provide the basis for preparing for and mitigating natural hazards.

Earth Science Week gained Congressional recognition on July 15 when Sen. Ron Wyden (D-Ore.) entered the Earth Science Week resolution into the Congressional Record. The resolution, issued by the Association of American State Geologists, designates the second week of October as Earth Science Week.


(From an AGI news release, July 15, 1998.)
Selected Additions to the Library of the Division of Geology and Earth Resources

March 1998 through July 1998

THESES


U.S. GEOLOGICAL SURVEY

Published Reports


Open-File and Water-Resources Investigations Reports


American Society of Civil Engineers, Seattle Section; University of
Trehu, A. M., 1997, Collaborative research (USGS/OSU/UTEP)—A
U.S. Geological Survey Contract Reports
Thomas, B. E.; Cox, S. E., 1998, Ground-water age, flow, and quality
Snyder, D. T.; Wilkinson, J. M.; Orzol, L. L., 1996, Use of a ground-
Munn, M. D.; McHenry, M. L.; Sampson, V., 1996, Benthic macroin-
Kimmel, R. M., 1998, Water, ice, and meteorological measurements

U.S. Geological Survey Contract Reports
Carpenter, J. E., 1996, Workshops to explain the changes resulting from seismic rezone from UBC Zone 2B to Zone 3 in southwest Washington State: U.S. Geological Survey contract report, 7 p.

OTHER REPORTS ON WASHINGTON GEOLOGY
American Society of Civil Engineers, Seattle Section; University of Washington Department of Civil Engineering; U.S. Geological Survey, 1998, Landslides in the Puget Sound region—Seminar: American Society of Civil Engineers, Seattle Section, 1 v.
Includes:
Mann, Glen, 1998, Costs and challenges of mitigating small-scale landslides. 31 p.
Morlan, L. E., 1998, Conclusions and recommendations followed by questions and answers to the speakers. [28 p., unpaginated.]

Peterson, John, 1998, A city’s perspective to the 1997 landslides. [47 p., unpaginated.]
Walker, Jim, 1998, City of Edmonds landslide policy and Meadowdale area case history. [46 p., unpaginated.]
Includes:
Includes:
Walsh, T. J., 1988, Session—National Tsunami Hazard Mitigation Program; Topic—Tsunami hazards in Washington. p. 35.
Huckell/Weinman Associates, Inc.; and others, 1995, Cadman Black Diamond mine pit expansion—Draft environmental impact statement: King County Department of Development and Environmental Services, 1 v.


Washington Department of Natural Resources, 1996, Hazel watershed analysis: Washington Department of Natural Resources, 1 v., 19 plates.


**PAPERS ON WASHINGTON GEOLOGY**


Bohmann, Gerhard; Greinert, Jens; Suess, Erwin; Torres, Marta, 1998, Authigenic carbonates from the Cascadia subduction zone and their relation to gas hydrate stability: Geology, v. 26, no. 7, p. 647-650.


Pelto, M. S., 1998, Changes in glaciers on Glacier Peak in the last 100 years: Mazama, v. 79, no. 13, p. 29, 39.


Scherer, George; Zabowski, Darlene; Everett, Richard, 1996, Nutrient content and survival of three native species on ameliorated abandoned copper mine tailings at Holden, WA: Association of Abandoned Mine Land Programs, 18th Annual Conference, p. 35-43.


**OTHER REPORTS OF INTEREST**


Includes:


Francis, Peter, 1997?, Volcanoes—A planetary perspective; Slide set: [Privately printed by the author], 8 p., 40 slides.


Includes:

Preuss, Jane; Priest, G. R., 1997, Tsunami hazard mitigation and counter measures with an example from Oregon, p. 43-46.


Kuroiwa, Julio; Zupka, Dusan, reviser; Schneider, Christine V., translator, 1995, Tsunamis—Population evacuation and land use planning for disaster mitigation; Localities studied in Peru (1981–1994): UNDHA, 1 v.


**REVISED USGS REPORT RELEASED**

Water Resources Investigations Report 92-4109, “Hydrology and quality of ground water in Northern Thurston County, Washington” has been revised and reissued. Copies of the original report should be destroyed. For further information contact Brian Drost, (253) 428-3600 x2642, or Gary Turney, x2626, at the USGS district office in Tacoma.


Washington Department of Natural Resources, 1997, Final habitat conservation plan: Washington Department of Natural Resources, 1 v.


Wolfberg, Donald; Reinarz, Patsy, 1997, Collecting the natural world—Legal requirements and personal liability for collecting plants, animals, rocks, minerals, and fossils: Geoscience Press, Inc., 329 p.

**Association of American State Geologists Present Results of STATEMAP Program**

Continued from page 2

The STATEMAP program is part of the National Cooperative Geologic Mapping Program, for which the U.S. Geological Survey is lead agency. Washington’s state geological survey is now in its third year of project work funded in part by the program. (See p. 58 for information about digital products.)

The reception was well attended. Many comments about the high quality of the work and interest in the program came from U.S. Geological Survey. This event certainly was a highlight in the history of the Association of American State Geologists.
DIVISION PUBLICATIONS

New Releases


Fossils in Washington

Information Circular 33, Fossils in Washington (please note: written in 1959, reprinted in 1983) is now out of print. However, we are making corner-stapled photocopies available for $1 each.

Federal Lands for Mineral Exploration and Development

In the process of moving our publications to a new storage area, we found several boxes of GM-30—Availability of federal lands for mineral exploration and development in the State of Washington. These maps show the various categories of federal land in Washington as they were in 1984. The federal government has not given up these lands since then, although some trades have taken place between DNR and the U.S. Forest Service on the Olympic Peninsula. In addition, the Yakima Firing Range (U.S. Army) has expanded north to I-90. The federal land parcels that are shown on GM-30 maps as restricted or unavailable remain so; the trend is to withdraw more federal land for endangered species or various ecological and other reasons. No more current map is available. We offer this report free, and you may request multiple copies.

(Orders must be prepaid. Make check or money order payable to the Department of Natural Resources. Taxes apply to Washington residents only. Please include $1.00 for postage and handling of orders to be sent by mail.)

Washington Bibliography Available on CD-ROM

The Digital Index to the Geology and Mineral Resources of Washington, 1798 through July 1998, compiled and edited by Connie J. Manson, is now available on CD-ROM. The file contains the citations and indexing for more than 32,000 items and includes both the items listed in our printed bibliographies and those non-Washington items held in our library. The disk contains the search software and runs on Windows 3.1 or higher. It sells for $3.22 + .28 tax (for Washington residents only) = $3.50. (Please include $1.00 postage and handling for each order.)

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If you supply your +4 digit, zip extension with your new address, it saves our staff a lot of time and makes the job of maintaining an accurate mailing list easier. There are several ways to contact us; look under Main Office in the left column on p. 2.