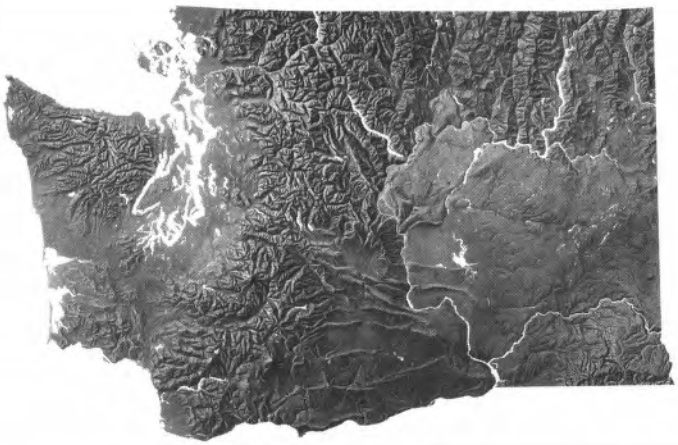

WASHINGTON GEOLOGY

Washington Department of Natural Resources, Division of Geology and Earth Resources Vol. 20, No. 3, September 1992

The East Side Pend Oreille mine surface plant in 1965, much as it appears today. The old West Side Pend Oreille surface plant, which is now flooded behind Boundary Dam, appears on the far right across the Pend Oreille River. The town of Metaline Falls and the Lehigh Portland Cement plant appear in the background. Aerial view from the north. Photo by Libby and Son, Spokane.

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WASHINGTON GEOLOGY

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National Geologic Mapping Act of 1992

by Raymond Lasmanis

As the economic and environmental interactions among nations become more complex and challenging, the need to solve problems that affect society on local, national, and global scales is increasing. A geological map provides essential basic information that can be used to locate and manage natural resources (including ground water), to protect the public from geologic hazards, and to assist in mitigation or clean up for those areas that have been contaminated by past industrial practices. For example, under Washington State's Growth Management Act, geological maps are needed to classify mineral resource lands and to identify geologically hazardous areas.

While the need for geologic maps has been accelerating across the nation, the overall production of these maps by the U.S. Geological Survey and the states has been decreasing since 1963. In Washington, we are currently preparing a strong geologic map base for the entire state through our 1:100,000-scale and 1:250,000-scale geologic map series. The first of these compilations was released in 1986, followed by the southwest quadrant map in 1987 and the northeast quadrant map in 1991. We are well into completing the southeast quadrant of the state.

In 1991, the Association of American State Geologists negotiated, prepared, and then caused to be introduced H.R. 2763, a National Geologic Mapping Act. Following congressional passage, President Bush signed the Act into law (Public Law 102-285) on May 18, 1992. (See text p. 32.) The law establishes a cooperative partnership among the states, the U.S. Geological Survey, and academia. The four components of the implementation plan of the Act are:

- Prioritized federal geologic mapping
- Geologic mapping support, including an electronic national geologic-map database
- State geologic mapping
- Geologic mapping education

Section 9 of the Act covers spending authorization for each component. At this time, P.L. 102-285 is moving through the Congressional appropriations process. Indications are that full funding, as authorized, will probably not take place. Instead, sufficient monies will probably be made available to get the National Cooperative Geologic Mapping Program under way. That will certainly be a welcome boost to our own geologic mapping program and should begin to provide better geologic map coverage for many parts of the nation.

Note: The following references offer some background information on the national need for geologic mapping.

Bhagwat, S. B.; Berg, R. C., 1991, Benefits and costs of geologic mapping programs in Illinois—The case of Boone and Winnebago Counties and its statewide applicability: Illinois State Geological Survey Open Files Series 1991-5, 57 p.

National Research Council Committee Advisory to the U.S. Geological Survey, 1987, Geologic mapping in the U.S. Geological Survey: National Academy Press, 22 p.

National Research Council Committee on Geologic Mapping, 1988, Geologic mapping; Future needs: National Academy Press, 84 p.

Re-evaluation of the Geology and Zn-Pb Ore Deposits of the Metaline Mining District, Northeastern Washington

by Jack A. Morton
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Metaline Falls, WA 99153

INTRODUCTION

The geologic setting and ore deposits of the Metaline mining district are reviewed and reinterpreted in this article on the basis of empirical data compiled during the past 70 years of mining and exploration at the district's major producer, the Pend Oreille mine. These observations were collected over the years by Pend Oreille Mines and Metals (1929–1974), Vanguard Exploration (1967–1974), The Bunker Hill Company (1974–1983), Gulf Resources and Chemical Exploration Co. (1974–1983), Pintlar Corp. (1983–1988), Resource Finance Inc. (1988–present), and Minnova Inc. (1991–present). The ore deposits are also compared to the similar but better known Mississippi Valley- and Irish-type deposits. A brief history of mining at the Pend Oreille mine is also included.

In the Metaline mining district, Zn-Pb ore deposits occur in carbonate rocks in the upper half of the Cambrian–Ordovician Metaline Formation. These deposits are among numerous carbonate-hosted Zn-Pb deposits in lower Paleozoic miogeoclinal rocks of the Kootenay arc in northeastern Washington and southeastern British Columbia. The locations of the Metaline district and the Pend Oreille mine are shown in Figure 1.

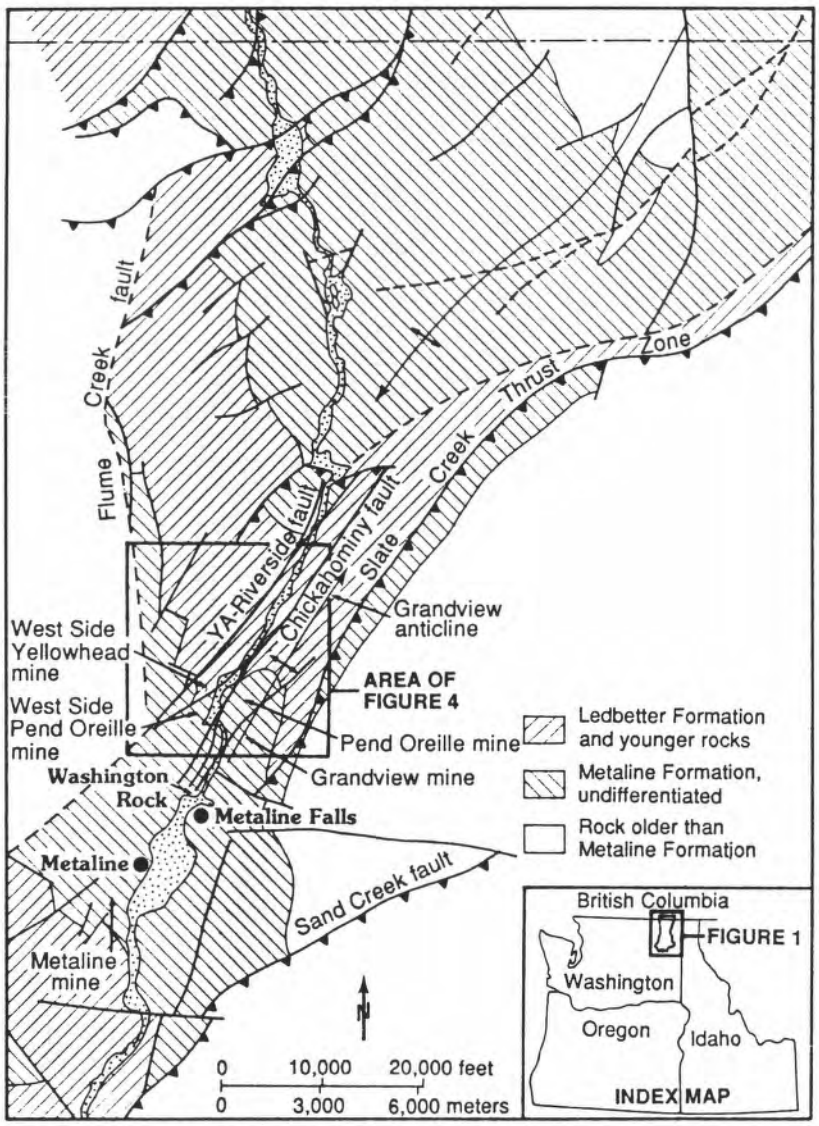

Figure 1. Generalized bedrock geology of the Metaline mining district. Modified from Dings and Whitebread (1965). The dotted area is the Pend Oreille River.

Two spatially separate types of stratabound and crudely stratiform, carbonate-hosted, Zn-Pb mineralization are recognized in the district (Fig. 2). Josephine mineralization, the most heavily exploited in the past, occurs as irregular, localized bodies of sphalerite and subordinate galena hosted by gray to black siliceous carbonate breccias in the uppermost 150 m of the Metaline Formation. The second type, and the object of recent and current interest, is Yellowhead mineralization, which occurs as blanket-like zones of pyrite at several stratigraphic positions from about 300 m to as much as 730 m below the top of the Metaline Formation. Yellowhead orebodies are localized accumulations of sphalerite and subordinate galena within the pyrite zones and are of higher grade and are more continuous than Josephine orebodies. Both types of mineralization have also been identified to the west in Stevens County (Mills, 1977; Neitzel, 1972) and Yellowhead mineralization was recognized in southeastern British Columbia by Mills (1974). Small amounts of mineralization that do not appear to belong to either of these types have also been noted, but only Josephine and Yellowhead types have produced significant tonnages in the Metaline district.

Josephine and Yellowhead orebodies closely resemble deposits that have been the principal source of Zn and Pb in North America: Mississippi Valley-type deposits. Another type of carbonate-hosted Zn-Pb deposit, the Irish type, also has much in common with Metaline ores, but may have a significantly different origin from the Mississippi Valley-type. This article briefly reviews the characteristics and genesis of Mississippi Valley-type and Irish-type deposits and compares them to the Metaline deposits.

GEOLOGIC SETTING

The aspects of the geologic setting of the Metaline ores discussed here have been useful in guiding recent exploration and development drilling. However, a comprehensive understanding of the ore deposits with respect to local and regional stratigraphy, paleogeography and depositional environments, sources of sediment, diagenesis, tectonics, and regional metamorphism has not been achieved. The stratigraphic interpretations of Bush and others (1992) are briefly reviewed here, with emphasis on those lithofacies that host mineralization. Some details of the overlying Ledbetter Formation are also given because they reflect sedimentary and mineralizing processes like those in the Metaline Formation.

Stratigraphy

The Metaline Formation ranges in age from Middle Cambrian to Middle Ordovician. In the Metaline district, the formation probably exceeds 1,800 m in thickness. It comprises six lithofacies units: thin-bedded lime mudstone, light-gray bedded dolostone, gray massive lime mudstone, varied dolostone, Josephine breccia, and Fish Creek breccia. See Bush and others (1992, fig. 2) for the stratigraphic relations of Metaline lithofacies. Throughout the district, these units are irregularly distributed vertically and horizontally and have boundaries that vary from even and conformable to steeply interfingered, disconformable, and locally discordant. No stratigraphic markers within the Metaline have been identified, and fossils are rare in most lithofacies. The Metaline in northern Pend Oreille and Stevens Counties differs from equivalent miogeoclinal rocks in southern Stevens County and northern Idaho and Montana in that it is as much as three times thicker, is stratigraphically more complex, and contains numerous Zn-Pb deposits.

In the region, four Metaline lithofacies host significant mineralization: light-gray bedded dolostone, varied dolostone, Fish Creek breccia, and Josephine breccia. The light-gray bedded dolostone is a "monotonous succession of non-fossiliferous gray to black, fine- to medium-grained, parallel bedded dolostone interlayered with massive, gray, featureless, fine- to medium-grained dolostone" (Bush and others, 1992, p. 5). It is thought to have been deposited in subtidal environments with local shoaling to intertidal and supratidal depths (Bush and others, 1992). The varied dolostone comprises a wide variety of dolomite, lime mudstone, and shale lithologies and is characterized by hummocky, lenticular, and disconformable bedding, abrupt lateral changes in lithology, and an abundance of clastic lithologies, including breccias. Bush and others (1992) concluded that the varied dolostone formed in poorly oxygenated, subtidal environments on a basin margin that was intermittently affected by storms, cut by tidal channels, and subjected to slumping.

The remaining two lithofacies make up the top of the Metaline Formation and consist in large part of breccias. The Josephine breccia (0–65 m thick) is an extremely heterogeneous assemblage of irregularly interbedded dark-gray to black, irregularly silicified, weakly pyritic and phosphatic, fragmental dolostones. Black, fine-grained dolostone and dolostone breccia are the more common lithotypes. The matrix-supported breccia fragments include carbonate, chert, quartzite, pyrite, and black argillite. Josephine breccias are irregularly interlayered with abundant gray dolostone, chert, lime mudstone, and black argillite. Boundaries between the Josephine and other Metaline units and the Ledbetter Formation vary from interbedded and gradational to interfingered and disconformable. McConnell and Anderson (1968) and Bush and others (1992) concluded that most lithologies of the Josephine breccia were deposited in anoxic basinal environments by slumps and debris flows.

The Fish Creek breccia lithofacies (as much as 365 m thick) is stratigraphically and lithologically similar to the Josephine unit and reflects similar depositional environments. It crops out in northern Pend Oreille and Stevens Counties, but not in the Metaline district. It is more homogeneous than the Josephine and consists of light- to dark-gray, fine- to medium-grained, thin-bedded dolostone and interbedded slump and debris flow breccias (Hurley, 1980; Fischer, 1984; Bush and others, 1992). The upper part contains abundant gray limestone and black shale and is conformable with and gradational into the Ledbetter Formation. Fish Creek breccias comprise gray, angular to subround dolostone fragments supported by dark-gray to black, weakly pyritic and phosphatic, fine-grained dolostone matrix, but unlike Josephine breccias, the fragments are mostly thin bedded. Clastic textures, graded bedding, disconformable bedding, and soft-sediment folds are common.

The recognition of lithologic and paleontologic gradation from the Josephine and Fish Creek breccias into the Ledbetter Formation (Bush and others, 1992; Carter, 1989a) has increased the importance of understanding basal Ledbetter rocks. Recently, core drilling in the central part of the Metaline district has provided a view of the base of the Ledbetter that has not been available in surface or underground exposures. Core samples reveal that the lowermost few hundred meters consist of the black, graptolitic, pyritic, and parallel-bedded argillite that typifies the Ledbetter throughout much of the region, but that the basal 20 meters

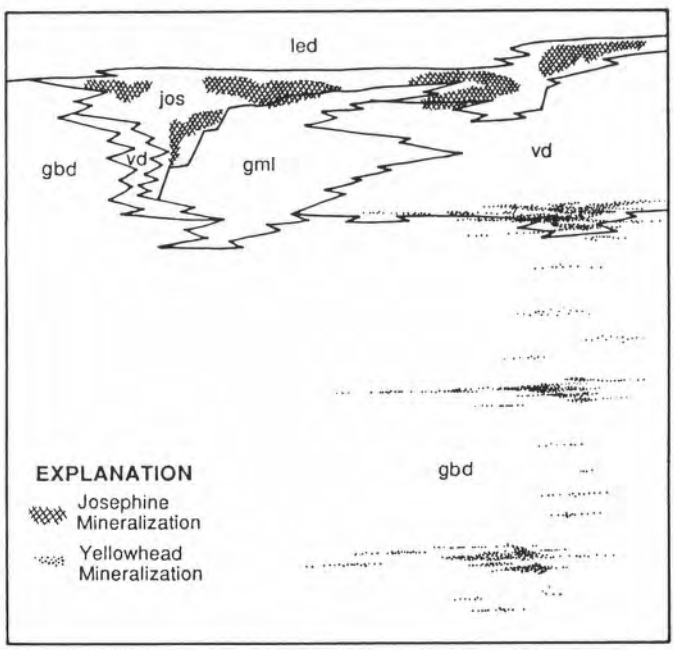

Figure 2. Diagram of the stratigraphic distribution of major sulfide mineralization in the Metaline Formation. Units: led, Ledbetter Formation; jos, Josephine breccia; gml, gray massive lime mudstone; vd, varied dolostone; and gbd, light-gray bedded dolostone.

also contains irregular lenses of debris-flow breccias. The breccias consist of sharply angular, wispy pulled-apart, or raggedly outlined fragments of dolomite, chert, quartzite, limestone, black argillite, and massive pyrite supported by black argillite matrix (Fig. 3a). The breccias are indistinguishable from breccias in the underlying Josephine and include occurrences of pale sphalerite in siliceous fragments. Similar, but unmineralized, breccias were recognized in the Ledbetter in the Metaline district by Dings and Whitebread (1965) and in the adjacent Salmo district of British Columbia by Fyles and Hewlett (1959). The recently drilled breccias accompany intraformational folds, truncated bedding, and internally disrupted beds.

The basal Ledbetter also contains numerous turbidite beds as much as 2 cm thick consisting of 10 percent or more light-gray rounded lime clasts in black argillite matrix. The clasts are of sand size near the contact with the Josephine, but decrease in size upward until they blend into the argillite matrix a few hundred meters above the contact.

Interbedded with the debris-flow breccias and turbidites are intervals of black argillite containing calcite-quartz-pyrite pseudomorphs after gypsum or anhydrite. The euhedral pseudomorphs measure as much as 2 cm on a side, are randomly oriented, and displace argillite bedding (Fig. 3b). Although gypsum and anhydrite are commonly thought of as "evaporites" formed in very shallow, hypersaline sea water, they are also recognized in modern deep-water sediments (Kendall, 1980) and as gangue minerals adjacent to active metal-rich hydrothermal vents on the sea floor (Blum and Puchelt, 1991). Consequently, while their occurrence in Ledbetter black argillite reflects hypersalinity, it does not represent shallow evaporative conditions.

Figure 3. Core showing typical lowermost Ledbetter lithologies. Pieces of core are 6.4 cm across; circular saw marks are visible on the core surface. 3a, Breccia consisting mostly of chert fragments with subordinate black argillite and pyrite fragments in black argillite matrix from 1 m above the contact with the Metaline Formation. The largest fragment on the lower left (at arrow) is black-gray-clear mottled chert containing 5 volume percent disseminated pale yellow sphalerite grains. 3b, Light-gray calcite-quartz-pyrite pseudomorphs of sulfate minerals in massive to laminated black argillite from 0.7 m above the contact.

Many studies of Metaline rocks considered them to have formed in shallow water on the carbonate platform that rimmed much of the North American craton during the early Paleozoic. Bush and others (1992), however, noted that the presence of debris-flow breccias, turbidites, intraformational folds, and truncated bedding indicated deposition in deeper and more unstable environments. They concluded that Metaline rocks formed at depths ranging from shallow to basinal at the seaward end of a carbonate ramp. Schuster and others (1989) had previously concluded that the occurrence of mixed deep- and shallow-water fossils in the gray massive lime mudstone was indicative of depositional environments at or near the continental margin. The abundance of black and dark-gray pyritic lithologies, the absence of fossils of bottom-dwelling organisms, and the presence of pseudomorphs of displacive (rather than transported) gypsum or anhydrite suggest that upper Metaline and lower Ledbetter environments were largely anoxic and, at times, hypersaline.

Bush and others (1992) considered that much of the complexity in Metaline stratigraphy and many of the abrupt lateral changes in lithofacies reflect syndepositional basin-margin faulting. Faulting may have produced oversteepened and unstable slopes between an anoxic deep-water basin and shallower environments that were the source of the sediment-gravity deposits in the upper Metaline and lower Ledbetter. The upward decrease in the grain size of lower Ledbetter turbidites indicates that relief between basinal and upslope environments persisted after the local Ledbetter/Metaline transgression in the early Middle Ordovician and that their topographically higher source became increasingly distant.

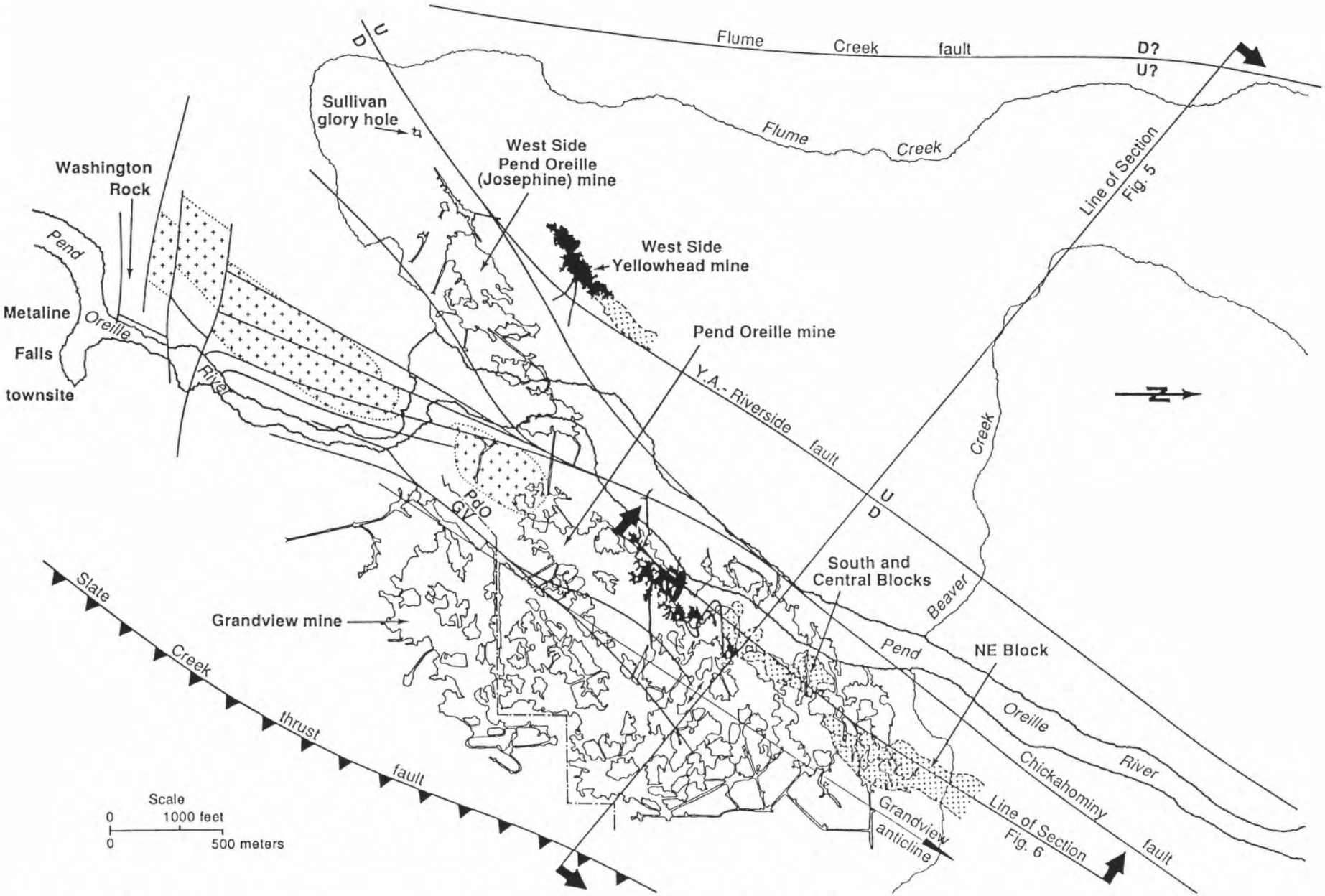

Figure 4. Plan view of Pend Oreille and adjacent mine workings. Josephine workings are shown open; Yellowhead workings (250–280 m below Josephine workings) are shown in solid black. The pattern of workings is simplified by the elimination of the pillars that make up about 25 percent of the area of the workings. Yellowhead drill-indicated reserves appear as the dotted pattern; areas of inferred Yellowhead ore (widely spaced drilling) appear as the plus-sign pattern.

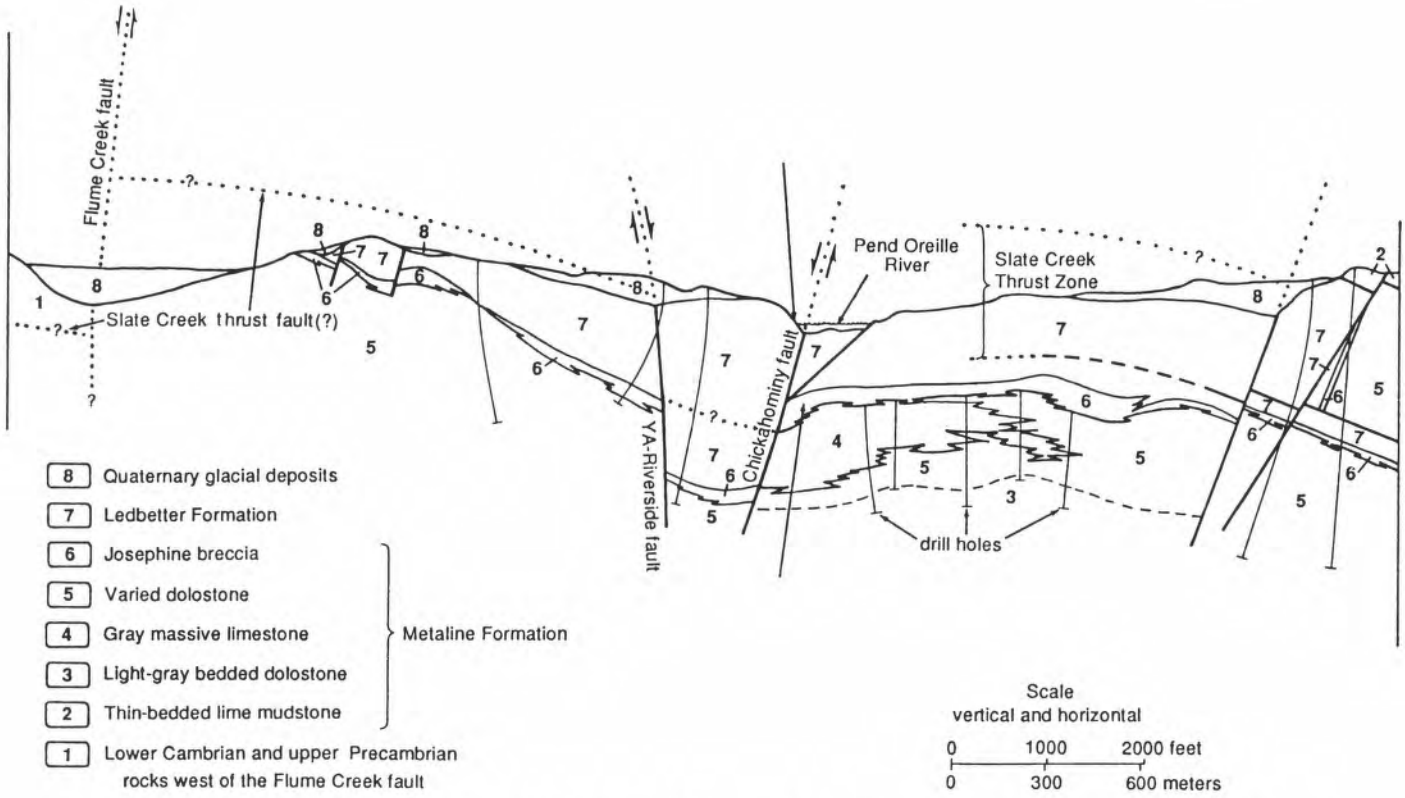

Figure 5. NW–SE geologic section across the Metaline mining district at the Pend Oreille mine. (See Fig. 4 for location of section.)

The fault-influenced complexity of upper Metaline stratigraphy is compounded further by the diagenetic conversion of much of the varied dolostone lithofacies to vuggy coarse-grained dolomite. Similarly, the original nature of much of the Josephine breccia is obscured by irregular, discordant bodies of jasperoid, calcite, quartz, and Zn and Pb sulfides that make up Josephine mineralization and ore.

Structure

Published interpretations have generally indicated that the Metaline district lies in a graben bounded by the Slate Creek and Flume Creek faults (Fig. 4). However, recent drilling, geologic mapping, paleontologic studies, and the review of core drilled in the 1960s suggest that the Slate Creek fault is a major east-dipping thrust and that thrusts are common in the district. Major normal faults are also more common and more continuous than previously recognized (Figs. 4 and 5). Much of the central part of the district is immediately underlain by highly contorted Ledbetter rocks in the Slate Creek thrust zone. This structure places Lower Ordovician Ledbetter rocks at the surface (Carter, 1989b) above Middle Ordovician Ledbetter and Metaline rocks 300 m below the surface in the Pend Oreille mine (Carter, 1989a).

Recognition of the Slate Creek fault as a thrust zone can influence re-interpretation of the Flume Creek fault, a major structure that some have suggested may be an east-side-down normal fault with displacement on the order of 3,700 m (Park and Cannon, 1943; Dings and Whitebread, 1965). If the rocks west of the Flume Creek fault lie above the western extension of the Slate Creek thrust, Flume Creek fault displacement can be accommodated by normal, west-side-down movement on the order of 600 m (Fig. 5). This sense of movement is similar to that of major normal faults that offset other thrusts in the district (Figs. 4 and 5).

MINERALIZATION

Josephine Mineralization

McConnell and Anderson (1968) provided thorough descriptions of the character and distribution of Josephine mineralization and ore in the Metaline district, and only a brief review is included here. Most orebodies consist of discordant breccias in which a matrix of locally vuggy, coarse-grained calcite-quartz-jasperoid with erratically scattered sphalerite and galena supports angular fragments of Josephine breccia and other Metaline lithofacies. Although the discordant breccias occur predominantly in and cut across Josephine lithofacies, they also locally transgress gray massive limestone and varied dolostone lithofacies (Fig. 2). Lesser amounts of ore lie in and along poorly defined faults that offset underlying rocks but do not offset the Josephine unit or the Ledbetter–Metaline contact. Orebodies take the form of irregular breccia pods vaguely elongate in a northeast direction and are tens to hundreds of meters across and hundreds to thousands of meters long. The deposit exploited by the Pend Oreille and Grandview mines has an amoeboid shape in plan and is made up of several individual orebodies (Fig. 4).

Discordant brecciation and mineralization are spatially associated with the most intensely silicified areas of the Josephine breccia lithofacies, but minor disseminated sphalerite is common throughout the lithofacies. In parts of some orebodies, fine-grained sphalerite is interbedded with black dolomite or argillite and has the appearance of a syngenetic sulfide sediment. As in lowermost Ledbetter breccias, fine-

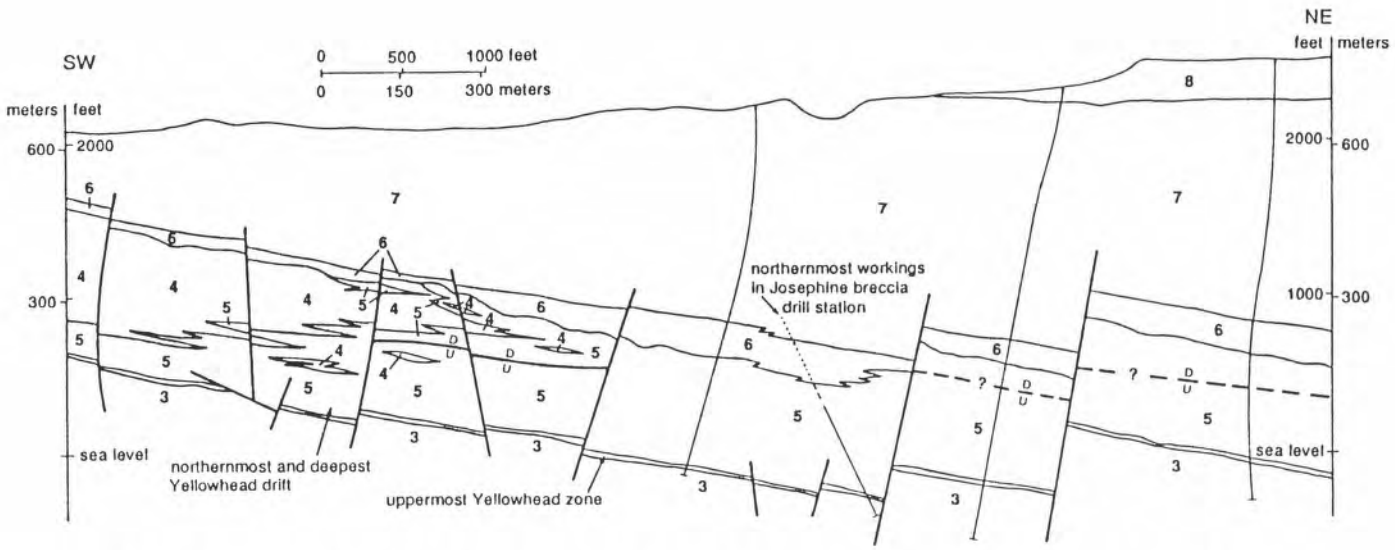

Figure 6. Longitudinal geologic section through the Pend Oreille mine. (See Fig. 4 for location; same units as Fig. 5.)

grained, disseminated, pale yellow or amber sphalerite is common in chert or quartzite fragments supported by unmineralized matrix in many areas of the Josephine lithofacies. Bending (1983) recorded fluid inclusion homogenization temperatures between 95° and 155°C for early-formed Josephine ore and as high as 228°C for later stages. Brown and Ahmed (1986) measured temperatures of 150° to 250°C for Josephine ore, but indicated that most were below 200°C. They also calculated the salinity of Josephine fluid inclusions at 15 to 23 weight percent NaCl equivalent.

Yellowhead Mineralization

Yellowhead mineralization can be described as the occurrence of a few percent to almost 100 percent fine- to coarse-grained pyrite in massive to diffuse lenses, pods, patches, and veins along crudely stratiform and stratabound zones in the dolostones of the upper half of the Metaline Formation. Individual zones vary from a few millimeters to more than 90 m thick, and some extend laterally for several kilometers. Even though Yellowhead zones consist predominantly of epigenetic sulfides that filled locally discordant open space, they are more laterally continuous than any carbonate lithofacies in the Metaline Formation and are commonly the only recognizable "stratigraphic" markers in the upper Metaline section. Traces of sphalerite and galena are common throughout the zones, but ore-grade accumulations of these minerals are restricted to north-northeast linear trends (Fig. 4) in which zone thickness and Zn and Pb content decrease away from the trend.

In the Pend Oreille mine, the top of the uppermost Yellowhead zone is approximately 300 m below the Ledbetter–Metaline contact at the irregular boundary between the varied and light-gray bedded dolostone units (Fig. 6). Core drilling in the mine has identified another Yellowhead zone about 490 m below the contact. In other areas, including the Washington Rock area (Figs. 1 and 4), ore-grade Zn-Pb mineralization is present in at least two Yellowhead zones in addition to the uppermost zone. The lower zones are stratigraphically separated from each other by 180 m to 250 m and occur in the light-gray bedded dolostone unit (Fig. 2). Although the Yellowhead zone exploited by the Pend Oreille mine is well established as the uppermost zone, the section above the West Side Yellowhead orebody has been eroded and its stratigraphic position remains unknown.

Within orebodies, Yellowhead zones generally comprise several Zn- and Pb-rich ore subzones interlayered with pyritic or dolomitic subzones containing little or no Zn or Pb (Fig. 7). In cross section, the ore subzones are irregularly lensoidal and vary unpredictably in thickness and grade. Interfingering and interlensing of subzones occurs within the orebody, at its upper and lower contacts, and along its perimeter. As a result of this internal complexity, geologically discrete sulfide or carbonate intervals can rarely be correlated between adjacent drill holes (Fig. 7). The zones themselves, however, are readily correlated, and the location and elevation of their intercepts can be predicted with precision.

In decreasing order of abundance, the principal Yellowhead minerals are: pyrite, dolomite, calcite, sphalerite, galena, phengite (magnesian muscovite), jasperoid, quartz, talc(?), and unidentified clays (Morton, 1974; Bending, 1983; Colligan, 1984). In the most intensely mineralized parts of the ore, sphalerite is almost exclusively pale yellow, but on the fringes of orebodies, red and orange sphalerite are also common. Bending (1983) measured sphalerite fluid inclusion homogenization temperatures of 95° to 155°C.

The ore consists of jumbled masses of chaotically intergrown colloform/cockade sulfides, carbonates, and silicates. These have confusing and commonly contradictory paragenetic relations that indicate the filling of open spaces created by dissolution of a lithified host. The jumbled masses occur in, and are intergrown with barren, coarse-grained, light-gray, sparry dolomite. This assemblage forms a vuggy matrix that supports rotated fragments of both the dolostone host and fragmented sulfide-carbonate rock. Internal sediment of fine-grained, laminated, black dolomite containing pyrite and sphalerite grains covers the bottom of many vugs in the matrix. Bedding of the internal sediments parallels that of the surrounding host, indicating that internal clastic sedimentation followed the chemical precipitation of the carbonate-sulfide matrix, but preceded deformation of the dolostone

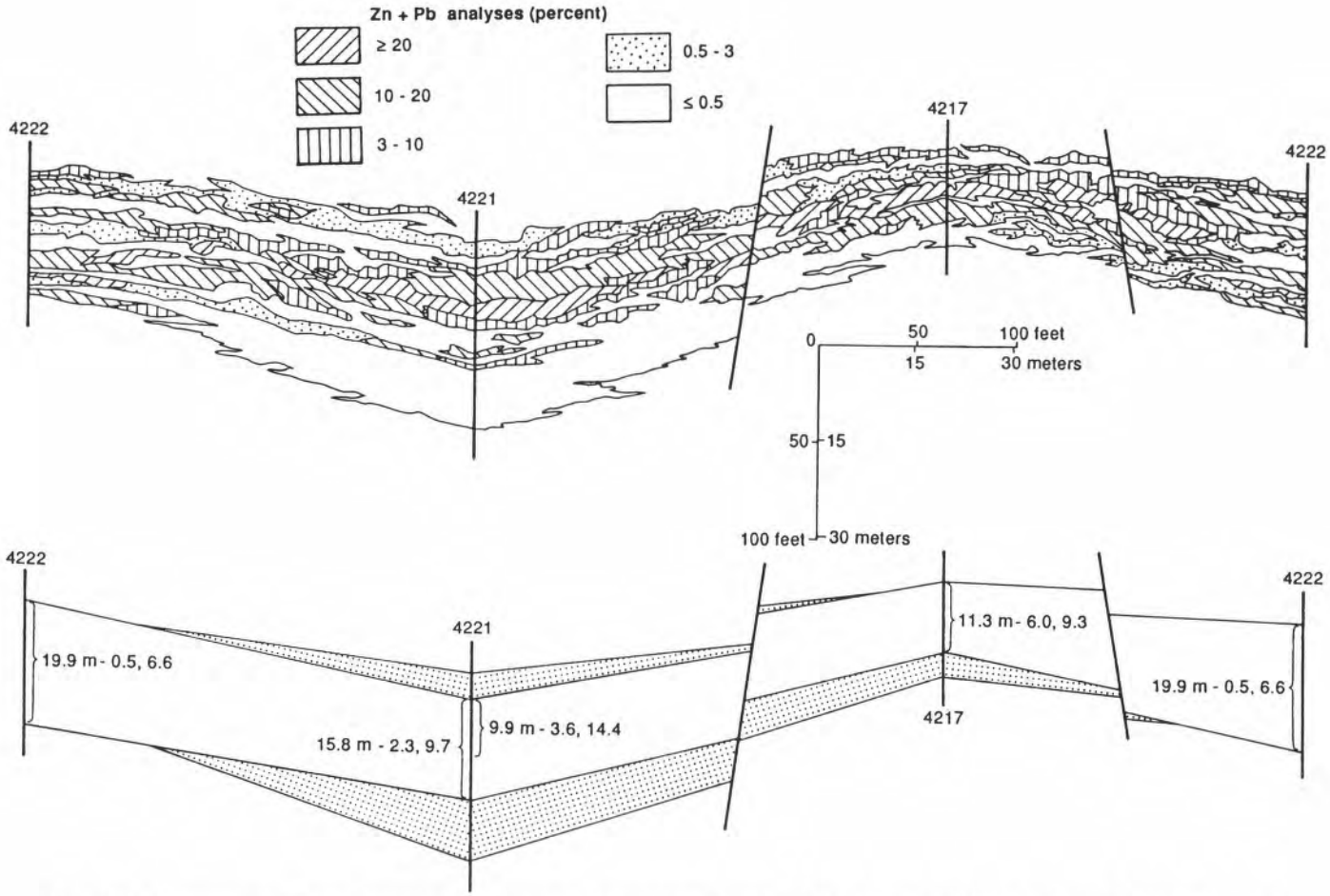

Figure 7. Diagrammatic section through the uppermost Yellowhead ore zone in the NE Block (see Fig. 4). Sectional panels between three adjacent high-grade drill holes are folded out to illustrate interlensing of ore and waste subzones (holes 4217, 4221, and 4222). Subzone configuration shown in the upper panels is hypothetical, but is based on configurations observed in wall mapping of both East and West Side Yellowhead workings. This figure illustrates the difficulty in correlating geologically discrete and separately assayed intervals in adjacent drill holes and in accurately predicting the grade of the deposit. Vertical thicknesses and composite (weighted) assays for the overall intercepts are shown in the lower panels. Values for thickness in meters are followed by percentages of Pb and Zn, respectively. Dotted pattern on lower panels represents pyritic rock containing little or no Pb or Zn.

host. A minor amount of Yellowhead ore occurs as replacement mineralization in the form of disseminated and massive sulfides that fade out laterally into the undisturbed dolomite host.

MISSISSIPPI VALLEY- AND IRISH-TYPE DEPOSITS

Many of the traits of Josephine and Yellowhead deposits are characteristic of Mississippi Valley (MVT)- and Irish-type deposits. These two types of deposits have much in common, but they are considered to have very different origins. MVTs[1] are stratiform, epigenetic, carbonate-hosted, Zn-Pb deposits that formed at depths of less than 1.5 km from brines with 15 to 25 weight percent NaCl equivalent (five to ten times the salt concentration of sea water) and that contained minor amounts of methane and petroleum. They were emplaced at temperatures between 100° and 150°C, too high for a "normal" shallow geothermal gradient, yet they show no relation to igneous heat sources. Individual districts have produced as much as 500 million tons of ore at grades ranging from 0.6 to 3.0 percent Pb and 2.3 to 7.0 percent Zn.

MVT deposits occur in shallow-marine carbonates at the peripheries of paleotopographic highs or broad upwarps in stable midcontinental regions, as well as in epicontinental platform carbonates. Dolostones are mineralized in preference to limestones, and the ore occurs in the matrix of reef, slump, tectonic, and solution-collapse breccias, and to a lesser extent in dilational veins and primary porosity. The simple ore-gangue mineralogy generally includes low-Fe sphalerite, Ag-poor galena, pyrite, and marcasite as the predominant sulfides, and dolomite, calcite, jasperoid, quartz, barite, gypsum, and anhydrite as the common gangue minerals. The ores are largely vuggy, colloform, and cockade and reflect the predominance of chemical precipitation in open spaces. Graded internal sulfide sediments (indicating clastic sedimentation) and some fine-grained replacement textures are also recognized. Fluid inclusion analyses indicate that MVT brines also contained minor methane and petroleum. Many MVTs have radiogenic Pb isotope ratios that yield irrational ages of emplacement (some of them in the future)

[1] Characteristics and genesis of MVTs are summarized here from Anderson, 1991; Briskey, 1986b and c; Heyl and others, 1974; Jackson and Beales, 1967; Mosier and Briskey, 1986; Russell and Skauli, 1991; and Sangster, 1976.

and preclude isotopic age-dating. Paleomagnetization studies, however, suggest that the deposits were emplaced less than 25 m.y. after lithification of their host. Pb- and S-isotope ratios have been interpreted as indications of multiple, shallow, crustal sources rather than deep-seated igneous sources.

The brines that deposited MVTs are generally thought to have originated as connate water trapped in basinal sediments. They scavenged metals from basinal shales and moved out of the basin under the influence of compaction, uplift, or tectonics. The brines carried the metals as chloride or organic complexes, but are not thought to have carried the H_2S necessary to form the metal sulfide deposits. They migrated into adjacent carbonates through the porosity created by the dolomitization of limestones. In the adjacent carbonates, high concentrations of H_2S in the pore fluids along favorable strata may have been generated by bacterial reduction of evaporitic sulfate, connate water sulfate, or organic matter and(or) thermal maturation of organics or hydrocarbons. Precipitation of MVT deposits would have occurred in the open spaces attendant to fault, slump, debris flow, and solution-collapse breccias where migrating metalliferous brines intersected H_2S-rich fluids.

This general model for MVT deposition has prevailed for decades, but recent studies (Bethke, 1986; Cathles and Smith, 1983; Deming and Nunn, 1991) have questioned the validity of some of its basic aspects. These studies indicate that heat flow, fluid flow rates, volume and composition of brine, and time necessary to form MVTs are not consistent with measured temperatures of deposition and salinities, nor with the calculated depths of emplacement. Deming and Nunn (1991) concluded that the model could only be effective if brines migrating regionally were "focused" or channeled by faults along basin margins. As a result, syndepositional and diagenetic faulting may assume more importance in future considerations of MVT genesis.

Irish-type deposits are also carbonate-hosted, stratiform Zn-Pb deposits, but they appear to be hybrids between epigenetic MVTs and syngenetic sedimentary-exhalative ores.[2] They occur in and along syndepositional faults where they take the form of discordant vein systems, replacement ore, and irregular but conformable lenses. They precipitated at between 100° and 350°C from brines with compositions similar to those of MVTs but lacking any trace of hydrocarbons. Some deposits occur near alkaline intrusives that may be genetically related. Individual Irish districts have produced as much as 150 million tons of ore at grades averaging about 3.0 percent Pb and up to 10 percent Zn.

The hosts for Irish-type ores are generally epicratonic limestones erratically intercalated with dolostones, sandstones, conglomerates, debris-flow and slump breccias, and dark-colored basinal shales. Abrupt changes in facies and thickness reflect control of host sedimentation by syndepositional faulting.

Irish-type ore mineralogy is complex compared to that of MVTs and consists of Fe-sulfide (pyrite, bravoite, and(or) marcasite in much greater amounts than are common in MVTs), low-Fe sphalerite, galena, chalcopyrite, bornite, chalcocite, tetrahedrite-tennantite, and a variety of other sulfosalts. Arsenopyrite, cinnabar, and native Ag are locally abundant. Common gangue minerals include barite, dolomite, calcite, chert/jasperoid, Fe-oxides, muscovite, gypsum, anhydrite, and minor fluorite. Ore and gangue minerals occur as granular, banded, colloform, or crustiform masses, as discordant fracture-fillings and stockworks, as laminated internal sediments, as disseminations in the host, and as fine-grained laminations intercalated in the host. These textures and lithologic relations indicate deposition by a combination of open-space filling, internal sedimentation, and replacement at the sea floor and in the unconsolidated to lithified sediments just below it.

The S-, O-, C-, and Pb-isotope compositions of the Irish ores have been interpreted as indicating deep-seated sources for the metals. Combined with evidence of control of ore deposition by synsedimentary faults, this suggests that basin margin faults extended deep enough to tap formation waters that picked up their metal content and much of their heat from deep-seated metamorphic and igneous sources. The similarities between MVTs and Irish-type deposits might be interpreted to suggest that the Irish ores simply represent MVT mineralizing systems that breach the sea floor. However, the higher temperatures of formation of Irish deposits, their complex metal composition and mineralogy, and their pronounced affiliation with active faulting suggest fundamentally different mineralizing systems.

CLASSIFICATION AND GENESIS OF METALINE ORES

Classification of Metaline deposits can affect geological perceptions of the ores and influence the manner in which they are explored for, developed, and financed. The preceding section illustrates many similarities between MVTs and Irish deposits but also some consistent distinctions. MVTs are mineralogically simple and were emplaced epigenetically at between 100° and 150°C. In contrast, Irish-type ores are mineralogically complex and were formed epigenetically and syngenetically at between 100° and 350°C.

The simple mineralogy of Josephine ores and the low-temperature deposition of its early stages suggest that they be included with MVTs. The low-temperature epigenetic character and simple mineralogy of Yellowhead deposits indicates that they too should be considered MVTs. However, the presence of both epigenetic and syngenetic components of Josephine mineralization, the chaotic stratigraphy and abundance of basinal facies of its host, the high temperature of its later stages, and the high pyrite content of Yellowhead mineralization are not characteristic of MVTs and are more typical of the Irish deposits. These factors suggest that Metaline ores formed from MVT solutions, but that they were emplaced in a tectonically active environment more typical of the Irish deposits. As such, they can be considered hybrid Mississippi Valley-type deposits and their peculiarities accommodated in a variation of the general MVT genetic model.

The earliest stage of Josephine mineralization, represented by Zn-mineralized siliceous fragments in both the Josephine breccia lithofacies and lower Ledbetter, indicate that early mineralization took place in the upslope source area of the clasts before brecciation and re-deposition. Layers of bedded fine-grained syngenetic sphalerite in the Josephine breccia lithofacies suggest that Zn mineralization also occurred in debris flow depositional environments. Although

[2] Characteristics and genesis of Irish-type deposits are summarized here from Badham, 1981; Boast and others, 1981; Briskey, 1986a; Evans, 1976; Hitzman and Large, 1986; and Stewart, 1984.

atypical of MVTs, this syngenetic component may result from an MVT system that reached the basin sea floor.

In contrast to the early and relatively small syngenetic component, most Josephine ore consists of jasperoid-sphalerite bodies that are partially discordant, that are associated locally with faults, and that formed by epigenetic filling of open spaces and replacement of the Josephine breccia lithofacies. The latest stage of mineralization, sphalerite-quartz-jasperoid-galena, accompanied formation of the extremely coarse-grained white calcite matrix of extensional collapse breccias that post-date Josephine and Ledbetter lithification. However, it is not clear if the latest stage is related to subsequent igneous, tectonic, or metamorphic events. As a result, the overall timing of Josephine mineralization is unclear (as with most MVTs). Nor is it clear whether the syngenetic and epigenetic components of Josephine mineralization reflect discrete temporal episodes or pulses within a mineralization continuum of long duration.

The great lateral extent of Yellowhead zones and the widespread evidence of epigenetic open-space filling within them indicate pronounced stratigraphic control of intrastratal solution and subsequent filling of open spaces by ore and gangue minerals. The occurrence of sulfate pseudomorphs in upper Metaline rocks suggests that the sedimentary precursor to the Yellowhead zones and the lithology that may have been dissolved was gypsum or anhydrite. The local dissemination of sulfides and their lateral gradation into the undisturbed dolostone host indicate that *in situ* replacement of the dolomite host occurred in addition to its dissolution. Fluid inclusion homogenization temperatures suggest that Yellowhead sulfides and early-formed Josephine sulfides had a common low-temperature source, such as metalliferous brines expelled from adjacent basinal shales. The higher temperatures indicated for later Josephine quartz may have been produced by the influx of hotter fluids at a greater depth of burial during orogeny or by the introduction of hot fluids unrelated to evolution of the basin margin. Later Josephine mineralization could represent either the addition of Zn and Pb from a deep igneous or metamorphic source or the remobilization of early-formed sulfides.

In spite of the significant differences between Yellowhead and Josephine mineralization and the absence of a physical or temporal link between them, several factors suggest that they are manifestations of a single mineralizing system: similar mineralogies, similar range of fluid inclusion homogenization temperatures, and the sub-parallel alignment of the long axes of individual Josephine orebodies with the long axes of Yellowhead ore trends along a near-vertical plane over a stratigraphic thickness of more than 730 m.

The Metaline district occupies a position at the change in paleoslope between the seaward end of a Middle Cambrian–Middle Ordovician carbonate ramp and an adjacent anoxic shale basin that may also be the continental margin. The anomalous thickness and stratigraphic complexity in the Metaline district also indicate a high rate of subsidence. Lower–Middle Ordovician sediments deposited at this location may have been subjected to basin-margin faulting in addition to their inherently unstable topographic/structural position. The clastic carbonates at the top of the Metaline would have provided a permeable zone for migration of metalliferous brines forced out of basinal muds. Block faulting along the basin margin may have served to further localize the migration routes of the brines. Major orebodies such as Josephine and Yellowhead deposits may have formed where basin margin faults intersected zones containing fluids rich in H_2S at the stratigraphic positions formerly occupied by sulfates.

MINING AND DEVELOPMENT

Josephine Ore

The majority of Pend Oreille mine workings exploit Josephine ore in the Josephine breccia lithofacies of the Metaline Formation. Most of the workings are on the west flank of the broad Grandview anticline that plunges about 12 degrees to the northeast (Fig. 1). Mining and milling of near-surface, oxidized ore began in 1915 on the west side of the Pend Oreille River. Initially, a glory hole (an open pit with a haulage tunnel at the bottom) was used in addition to exclusively underground workings. The broken ore and waste were hauled to the surface through a network of near-horizontal rail tunnels connecting a series of hoists and inclined shafts. The workings were driven eastward and downward and crossed under the river in the 1940s. By 1950, most ore was being mined on the east side of the river and hauled underground to the mill on the west side.

Ore was concentrated at two successive mills on the west side of the river before the present 2,400-ton-per-day East Side mill was completed in 1952. (See cover photo.) At that time, the mine converted from rail haulage to diesel-powered track and rubber-tired equipment (Fig. 8), and a 1,935-m conveyor belt was built to bring ore and waste to the surface from an underground crusher. These changes increased production and decreased the cost of mining low-grade ore at increasing depths. Mining of Josephine ore continued with few interruptions until a strike at its smelter in Kellogg, ID, forced The Bunker Hill Co. to suspend its Pend Oreille operations in May 1977. By then, the mine had produced about 14 million tons of Josephine ore grading 1.3 percent Pb and 3.0 percent Zn and had 140,000 tons of indicated reserves at 0.5 percent Pb and 6.6 percent Zn.

Yellowhead Ore

By the turn of the century, several small underground operations had explored pyritic Yellowhead exposures along the Pend Oreille River. Development of these deposits continued sporadically but was overshadowed by the discovery of large Josephine orebodies. Mining efforts were further stifled by the low Pb content of Yellowhead ore and by the inability of the district's early mills to effectively separate the pyrite from the Zn and Pb sulfides. As a result, Yellowhead production was negligible until full-scale mining began at the West Side Yellowhead mine in 1971. The ore was mined with diesel equipment and the random-room-and-pillar method which left about 25 percent of the deposit as pillars to support the mine roof. By 1977, about 80 percent of the Pend Oreille mill's feed came from two Yellowhead deposits: the West and East Side Yellowhead orebodies.

The West Side Yellowhead deposit is exposed at the surface and was initially developed by shallow drilling in the late 1920s. Test mining in the 1920s and 1940s and surface diamond drilling in the 1960s and 1970s helped define the deeper parts of the orebody. Mining began in 1971 and the ore was trucked 6 mi by highway to the East Side mill across the river. By the 1977 shutdown, the West Side Yellowhead

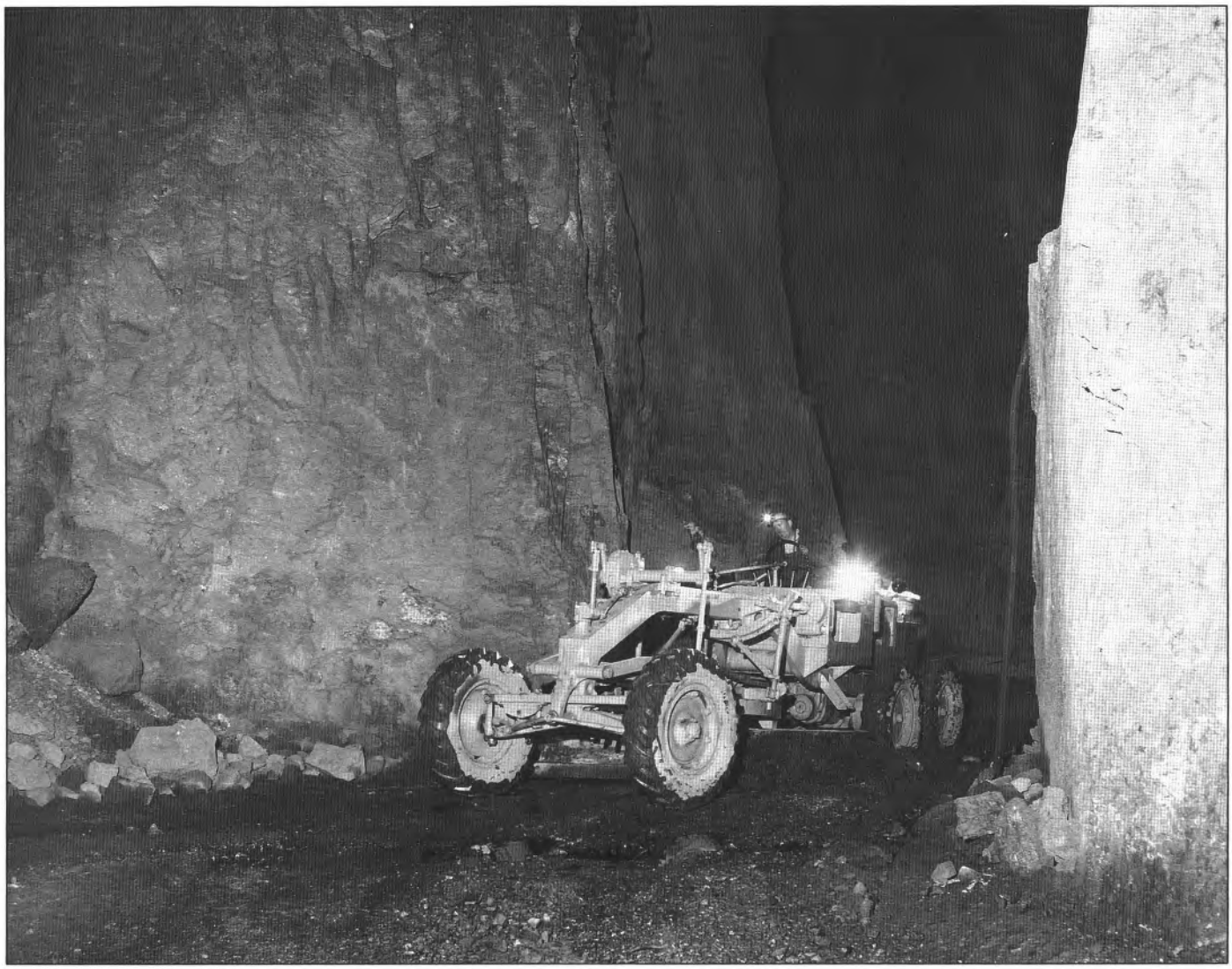

Figure 8. Motor grader leveling the roadway through a mined area on the 2200 level of the Pend Oreille mine in 1956. Photo by Caterpillar Tractor Co., Peoria, IL.

mine had produced 387,000 tons at 0.5 percent Pb and 4.0 percent Zn. It also had indicated reserves of 490,000 tons grading 0.3 percent Pb and 4.7 percent Zn that had been developed by drilling and drifting.

At the same time that Yellowhead mining began on the west side of the river, an inclined roadway was driven in the Pend Oreille mine to the uppermost Yellowhead zone where an orebody had been partially delineated by diamond drilling from the Josephine workings 200–275 m above. Random room and pillar mining began in that zone in 1972, and ore and waste were trucked up the roadway to the crusher at the bottom of the conveyor in the Josephine workings. By 1977, about 400,000 tons of ore had been mined at an average grade of 0.7 percent Pb and 3.7 percent Zn. About 6.5 million tons of inferred reserves grading 1.4 percent Pb and 6.1 percent Zn had been developed by drifting and by underground and surface drilling. By that time, Yellowhead deposits had been demonstrated to be more continuous and of higher grade than Josephine deposits, and they had become the object of most exploration in the Metaline district.

Recent Mine Development

Between 1977 and 1986, Bunker Hill, Pintlar, and GRC Exploration continued district exploration and operated pumps to prevent the 360-gal/min influx of ground water from flooding the mine. From 1986 to 1988, however, the mine was allowed to flood, and development was discontinued. Resource Finance Inc. (RFI) obtained an option-purchase agreement from Pintlar in 1988 and dewatered the mine, drilled more than 20,400 m in 60 holes from the surface and underground, and commissioned a feasibility study for mining and milling ore from the East Side Yellowhead deposit. In May 1990, RFI purchased the mine and mill along with 13,000 acres of contiguous mineral holdings in the district. Between February and June 1991, RFI drilled 7,000 m in 13 holes from underground to extend incompletely delineated reserves at the northeast end of the East Side Yellowhead deposit

(Fig. 4). RFI and Minnova recently completed 5,000-m of underground core drilling in 14 holes. The drilling confirmed the continuity of ore-grade mineralization in the NE Block, and it outlined a central core zone of a minimum 10 percent Zn over 3 m.

Ore Reserves

RFI and Minnova drilling programs over the past 3 years have defined the following indicated reserves in the East Side Yellowhead deposit:

	Short Tons	Pb	Zn	Average Thickness
NE Block	2,100,000	1.2%	11.2%	4.3 m
Central/SW Zones	1,350,000	2.3%	10.4%	3.8 m
AVERAGE	3,450,000 (total)	1.9%	10.9%	4.1 m

These reserves were calculated using a minimum of 5 percent Zn over a 1.7-m vertical thickness; Pb values were not considered.

Core drilling intercepts in the NE Block are significantly thicker and of higher grade than those in the previously mined areas of the deposit. Vertical thicknesses of as much as 15 m at more than 5 percent Zn and grades as high as 18 percent Zn and 3 percent Pb over 4.6 m have been intersected. At present, however, there is insufficient information to predict the production grade that could be maintained in either the high-grade areas or the deposit as a whole.

The estimation of production grade involves determining the amount by which the grade of ore is lowered by the unavoidable mixing of ore and low-grade or barren material. This "dilution" of the *in situ* grade estimated from drill holes is inherent in most mining operations, but the amount of dilution depends on the configuration, character, and orientation of the deposit and the mining methods used. Historic production grades for the East and West Side Yellowhead deposits are less than half the *in situ* grades calculated from drill intercepts (more than 100 percent dilution, or the equivalent of mixing ore with a slightly larger amount of barren waste). In the mined area of the East Side Yellowhead deposit, for example, geostatistical estimation of the average grade yielded values of 1.8 percent Pb and 7.3 percent Zn, but production grades there averaged only 0.7 percent Pb and 3.7 percent Zn. These low production grades may have been caused by mining practices that were not ideally suited to the orebody and that resulted in excessive dilution. However, some of the lowered grade may have resulted from the inability of the process of estimating *in situ* grade to account for internal and peripheral waste that could not be separated from ore, even under the most ideal circumstances.

Future Mining and Development

Resumption of production at the Pend Oreille mine hinges on the determination of a realistically sustainable mining grade of the East Side Yellowhead deposit. The higher grades and greater thicknesses of the ore in large parts of the deposit (particularly the NE Block) relative to those in the previously mined areas suggest that profitable mining is possible at present reserve tonnages. However, it is also probable that the present incompletely delineated East and West Side Yellowhead reserves can be extended outward along the ore trends in which they occur (Fig. 4). There is also a good possibility that similar orebodies occur in deposits that are similarly aligned but in other parts of the district than the two already developed. Mining and milling of high-grade Yellowhead ore in the NE Block and rehabilitating the Pend Oreille mine and mill infrastructure could eventually allow the profitable mining of some of the lower grade Yellowhead and Josephine reserves.

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REFERENCES CITED

Anderson, G. M., 1991, Organic maturation and ore precipitation in southeast Missouri: Economic Geology, v. 86, no. 5, p. 909-925.

Badham, J. P. N., 1981, The origins of ore deposits in sedimentary rocks. *In* Tarling, D. H., editor, Economic geology and geotectonics: John Wiley and Sons, p. 149-191.

Bending, D. A. G., 1983, A reconnaissance study of the stratigraphic and structural setting, timing, and geochemistry of mineralization in the Metaline district, northeastern Washington, U.S.A.: University of Toronto [Toronto, Ontario] Master of Science thesis, 324 p.

Bethke, C. M., 1986, Hydrologic constraints on the genesis of the upper Mississippi Valley mineral district from Illinois Basin brines: Economic Geology, v. 81, no. 2, p. 233-249.

Blum, N.; Puchelt, H., 1991, Sedimentary-hosted polymetallic massive sulfide deposits of the Kebrit and Shaban Deeps, Red Sea: Mineralium Deposita, n. 26, p. 217-227.

Boast, A. M.; Coleman, M. L.; Halls, C., 1981, Textural and stable isotopic evidence for the genesis of the Tynagh base metal deposit, Ireland: Economic Geology, v. 76, no. 1, p. 27-55.

Briskey, J. A., 1986a, Descriptive model of sedimentary exhalative Zn-Pb (Model 31a). *In* Cox, D. P.; Singer, D. A., editors, Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 211-215.

Briskey, J. A., 1986b, Descriptive model of southeast Missouri Pb-Zn (Model 32a). *In* Cox, D. P.; Singer, D A., editors, Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 220-221.

Briskey, J. A., 1986c, Descriptive model of Appalachian Zn (Model 32b). *In* Cox, D. P.; Singer, D. A., editors, Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 222-223.

Brown, P. E.; Ahmed, G. A., 1986, A petrographic and fluid inclusion comparison of silver-poor and silver-rich zinc-lead ores, N.E. Washington State: Mineralium Deposita, v. 21, no. 2, p. 156-163.

Bush, J. H.; Morton, J. A.; Seward, P. W., 1992, Depositional and stratigraphic interpretations of the Cambrian and Ordovician Metaline Formation, northeastern Washington: Washington Geology, v. 20, n. 1, p. 27-35.

Carter, Claire., 1989a, A Middle Ordovician graptolite fauna from near the contact between the Ledbetter Slate and the Metaline Limestone in the Pend Oreille mine, northeastern Washington State. *In* Sando, W. J., editor, Shorter contributions to paleontology and stratigraphy: U.S. Geological Survey Bulletin 1860, p. A1-A23.

Carter, Claire, 1989b, Ordovician–Silurian graptolites from the Ledbetter Slate, northeastern Washington State. *In* Sando, W. J., editor, Shorter contributions to paleontology and stratigraphy: U.S. Geological Survey Bulletin 1860, p. B1-B29.

Cathles, L. M.; Smith, A. T., 1983, Thermal constraints on the formation of Mississippi Valley-type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis: Economic Geology, v. 78, no. 5, p. 983-1002.

Colligan, T. H., 1984, Mineralization, deformation, and host rock diagenesis of the Upper Yellowhead zinc deposit: University of Washington Master of Science thesis, 64 p.

Deming, D.; Nunn, J. A., 1991, Numerical simulation of brine migration by topographically driven recharge: Journal of Geophysical Research, v. 96, no. B2, p. 2485-2499.

Dings, M. G.; Whitebread, D. H., 1965, Geology and ore deposits of the Metaline zinc-lead district, Pend Oreille County, Washington: U.S. Geological Survey Professional Paper 489, 109 p., 6 pl.

Evans, A. M., 1976, Genesis of Irish base-metal deposits. *In* Wolf, K. H., editor, Handbook of strata-bound and stratiform ore deposits; II. Regional studies and specific deposits; Vol. 5, Regional studies: Elsevier Scientific Publishing Company, p. 231-256.

Fischer, H. J., 1984, Pelagic and gravity sedimentation on the foreslope of a prograding Cambrian peritidal complex [abstract]: Society of Economic Paleontologists and Mineralogists Midyear Meeting Abstracts, p. 32.

Fyles, J. T.; Hewlett, C. G., 1959, Stratigraphy and structure of the Salmo lead-zinc area: British Columbia Department of Mines Bulletin 41, 162 p., 9 pl.

Heyl, A. V.; Landis, G. P.; Zartman, R. E., 1974, Isotopic evidence for the origin of Mississippi Valley-type mineral deposits—A review: Economic Geology, v. 69, no. 6, p. 992-1006.

Hitzman, M. W.; Large, D., 1986, A review and classification of the Irish carbonate-hosted base metal deposits. *In* Andrew, C. J.; Crowe, R. W. A.; Finlay, S.; Pennell, W. M.; Pyne, J. F., editors, Geology and genesis of mineral deposits in Ireland: Irish Association for Economic Geology [Dublin, Ireland], p. 217-238.

Hurley, B. W., 1980, The Metaline Formation–Ledbetter Slate contact in northeastern Washington: Washington State University Doctor of Philosophy thesis, 141 p.

Jackson, S. A.; Beales, F. W., 1967, An aspect of sedimentary basin evolution—The concentration of Mississippi Valley-type ores during late stages of diagenesis: Bulletin of Canadian Petroleum Geology, v. 15, no. 4, p. 383-433.

Kendall, A. C., 1980, Subaqueous evaporites (Facies model 14). *In* Walker, R. G., editor, Facies models: Geoscience Canada Reprint Series 1, p. 159-174.

McConnell, R. H.; Anderson, R. A., 1968, The Metaline district, Washington. *In* Ridge, J. D., editor, Ore deposits of the United States, 1933–1967; The Graton-Sales Volume: American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 2, p. 1460-1480.

Mills, J. W., 1974, Galena-bearing pyrite nodules in the Nelway Formation, Salmo, British Columbia: Canadian Journal of Earth Science, v. 11, n. 4, p. 495-502.

Mills, J. W., 1977, Zinc and lead ore deposits in carbonate rocks, Stevens County, Washington: Washington Division of Geology and Earth Resources Bulletin 70, 171 p.

Morton, J. A., 1974, The Yellowhead zinc-lead deposit—Origin, post-depositional history, and comparisons with similar deposits in the Metaline mining district, Washington: Washington State University Master of Science thesis, 159 p.

Mosier, D. L.; Briskey, J. A., 1986, Grade and tonnage model of southeast Missouri Pb-Zn and Appalachian Zn deposits. *In* Cox, D. P.; Singer, D. A., editors, Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 224-226.

Neitzel, T. W., 1972, Geology of the Van Stone mine, Stevens County, Washington: Washington State University Master of Science thesis, 47 p.

Oliver, J., 1986, Fluids expelled tectonically from orogenic belts—Their role in hydrocarbon migration and other geologic phenomena: Geology, v. 14, no. 2, p. 99-102.

Park, C. F., Jr.; Cannon, R. S., Jr., 1943, Geology and ore deposits of the Metaline quadrangle, Washington: U.S. Geological Survey Professional Paper 202, 81 p., 6 pl.

Russell, M. J.; Skauli, H., 1991, A history of theoretical developments in carbonate-hosted base metal deposits and a new tri-level enthalpy classification: Economic Geology Monograph 8, p. 96-116.

Sangster, D. F., 1976, Carbonate-hosted lead-zinc deposits. *In* Wolf, K. H., editor, Handbook of strata-bound and stratiform ore deposits; II. Regional studies and specific deposits; Vol. 6, Cu, Zn, Pb, and Ag deposits: Elsevier Scientific Publishing Company, p. 447-454.

Schuster, J. E.; Repetski, J. E.; Carter, Claire; Dutro, J. T., Jr., 1989, Nature of the Metaline Formation–Ledbetter Formation contact and age of the Metaline Formation in the Clugston Creek area, Stevens County, Washington—A reinterpretation: Washington Geologic Newsletter, v. 17, no. 4, p. 13-20.

Stewart, Taylor, 1984, Structural and paleotopographic controls of lead-zinc mineralization in the Silvermines orebodies, Republic of Ireland: Economic Geology, v. 79, no. 3, p. 529-548.

Editor's Note: This article appears as a companion to a study of the stratigraphy of the Metaline Formation by Bush and others (1992). ■

New USGS Volcanic Hazards Project

Thomas J. Casadevall, whose office is in Denver, CO, has started work on a new project to help aircraft to avoid areas affected by volcanic eruptions and to improve understanding of the relation between ash type (size, composition, and gas content) and damage in aircraft engines to help engine manufacturers determine what modifications could be made. He will be working with NOAA remote-sensing agencies to track volcanic ash clouds that drift away from their sources, with the FAA and international air-space controllers to improve procedures for delivering information about volcanic hazards, and with the FAA and airports authorities to develop recommendations for cleaning ash-contaminated facilities and aircraft to assure safe operations.

This project grew out of unexpected encounters with ash clouds in which large commercial aircraft suddenly lost power and suffered major and costly engine damage, in addition to threatening the lives of passengers. Volcanic ash clouds are not now detectable by aircraft in flight.

In the first year of his project, Casadevall will continue to analyze engine deposits and finish editing the volume of papers that report on the First International Symposium on Volcanic Ash and Aviation Safety, planned for release as a USGS bulletin. (See *Washington Geology*, v. 19, no. 3.) He will also be involved with educating aircraft crews, flight controllers, airline managers, and engine manufacturers through lectures, videos, and simulator training.

For more information about this project, please contact T. J. Casadevall, U.S. Geological Survey, Federal Center, MS 903, Denver, CO 80225; 303/236-1080.

Insects of the Klondike Mountain Formation, Republic, Washington

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Records of Tertiary insects in North America have appeared in the literature for more than a century (for example, Scudder, 1890; Cockerell, 1915; Wilson, 1977; Kevan and Wighton, 1983; Lewis, 1989). A recent search of this literature shows that at least 133 sites are known in 17 states, and insects from several more sites in Canada have also been reported (Lewis and Heikes, 1991). Almost half of these sites are in rocks of Eocene age, and most of the Eocene localities (Lewis, 1989) are concentrated in Colorado and Wyoming (Fig. 1). Until recently, little study has been focused on the Eocene insects of Washington.

The lakebed strata of the Republic area are a bonanza for students of fossil insects. Through early 1992, these middle Eocene rocks have yielded at least 546 insect specimens, now available for study at the University of Washington's Thomas Burke Memorial Washington State Museum in Seattle, St. Cloud State University in St. Cloud, MN, and the Stonerose Interpretive Center in Republic. These specimens encompass at least 13 extant orders and 27 families (Table 1). The fossils represent both adult and immature forms of aquatic and terrestrial insects. The most common fossils are specimens representing an order that includes the spittlebugs, leafhoppers, and aphids (Homoptera) and an order that is made up of the true flies (Diptera). Each of these orders represents about 30 percent of the fossil fauna. Table 1 indicates the abundance of each group.

The Republic site has yielded the earliest Eocene records (ca 49 million years) for North American mayflies (Ephemeroptera) and earwigs (Dermaptera). Another first is the fossil record of beetle eggs deposited on leaves (Lewis and Carroll, 1991).

Most Republic insects are preserved by carbonization, a process in which carbon images or impressions remained as the insects slowly decayed under water. When the rock is split open, commonly both the impression and its counterpart are revealed. Having both representations of the specimen has been very helpful to researchers.

There is both direct and indirect evidence of insects at Republic. Direct evidence consists of the fossil wings and(or) body parts; wings are the most abundant traces (Plates 1 and 2). Among the many virtually complete specimens is a moth. (See Joseph, 1986.) Indirect evidence includes: the larval cases that enclosed immature insects; eggs deposited on leaves; leafcutter bee damage to *Prunus* leaves by chewing (Plate 3), mining, and skeletonization.

Table 1 compares faunas of other Eocene localities in the United States with those of the several sites in the Republic area. The localities in British Columbia and Washington are geologically and geographically similar—the sites at Republic and Princeton, B.C., represent upland lakes in volcanic terrain. Tertiary insect faunas for the western United States are also broadly similar at the family level.

Paleoenvironmental interpretation of the Republic localities is still in its infancy. It may be too early to state with certainty that both the Eocene insects and plants lived in precisely the same kinds of habitats as their modern descen-

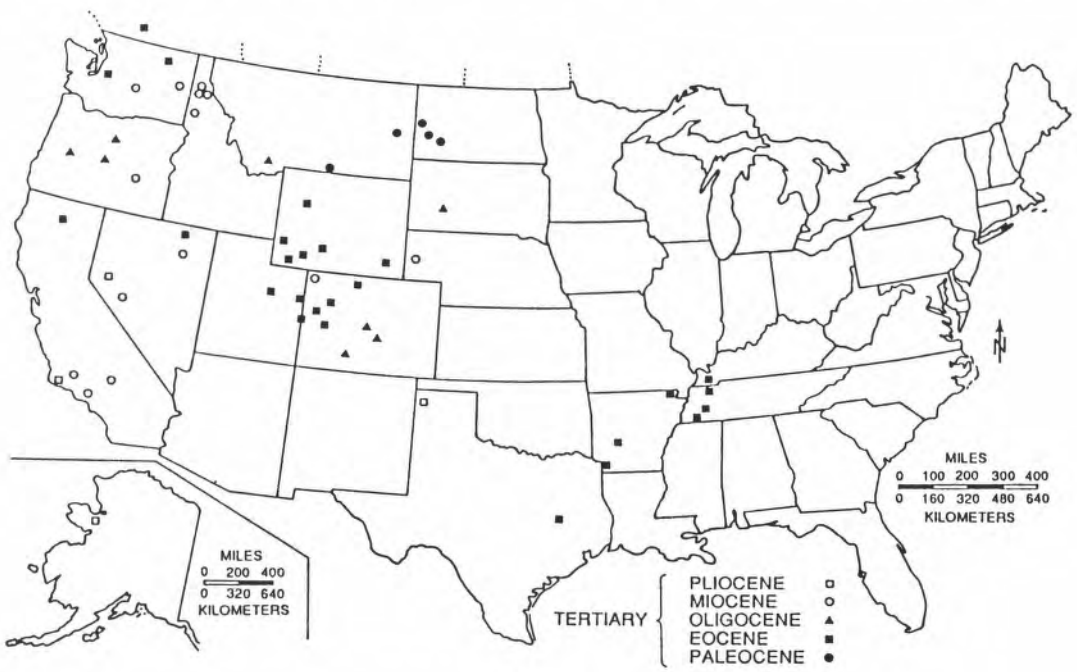


Figure 1. Geographic distribution of Tertiary insect localities in the United States.

Table 1. Fossil insects found at Republic sites; ( ), number of specimens; †, order found at Eocene sites in other states or provinces (see Fig. 1); AR, Arkansas; CA, California; CO, Colorado; KY, Kentucky; NV, Nevada; TN, Tennessee; UT, Utah; TX, Texas, WY, Wyoming; BC, British Columbia

Order	Family and genus	Common name	Modern habitat	†Other occurrences
Ephemeroptera	Heptageniidae (1)	mayflies	Streams and ponds	
	Unknown family (3)			
Odonata	Zacallitidae (2)	dragonflies	Streams and ponds	CA, CO, TX, BC
	Unknown family (3)			
Orthoptera	Blattoidea (3)	cockroaches	Terrestrial (wooded areas)	AR, CO, WY, BC
	Acrididae (1)	grasshoppers	Terrestrial (meadows)	
	Unknown family (4)			
Dermaptera	Forficulidae (2)	earwigs	Terrestrial (grasses, sedges, roots)	
Isoptera	Unknown family (5)	termites	Terrestrial (wooded areas)	TN, BC
Hemiptera	Pentatomidae (2)	stink bugs	Terrestrial (grasses)	AR, CO, WY, BC
	Unknown family (5)			
Homoptera	Cercopidae	spittlebugs, froghoppers.	Forests (pests on pines)	AR, CO, TN, WY, BC
	Palecphora (3)			
	Aphrophora (13)			
	Petrolystra (5)			
	Unknown genus (80)			
	Aphididae (2)	aphids	Plant feeders	
	Fulgoroidea (8)	planthoppers	Plant feeders	
Neuroptera	Unknown family (1)	dobsonflies, lace wings, etc.	Adults terrestrial	CO, BC
Coleoptera	Dytiscidae (1)	diving beetles	Streams and ponds	AR, CO, NV, TN, UT, WY, BC
	Carabidae (4)	ground beetles	Terrestrial (under stones, logs)	
	Elateridae (1)	click beetles	Terrestrial (on plants, under bark)	
	Lucanidae (1)	stag beetles	Terrestrial (wooded areas)	
	Cerambycidae (1)	round-headed borers	Tree borers	
	Chrysomelidae (7)	leaf beetles	Forests (pests on alders)	
	Curculionidae (5)	weevils	Plant feeders and plant pests	
	Unknown family (25)			
Trichoptera	Phryganeidae (5)	caddisflies	Streams and ponds	AR, CO, TN, WY, BC
	Limnephilidae (7)	caddisflies	Streams and ponds	
	Unknown family (13)			
Lepidoptera	Geometridae (1)	measuringworms	Terrestrial	CO, WY
	Unknown family (10)			
Diptera	Tipulidae (3)	crane flies	Damp areas with abundant vegetation	AR, CO, TN, UT, WY, BC
	Bibionidae (118)	march flies	Terrestrial (flowers)	
	Mycetophilidae (3)	fungus gnats	Damp areas with decaying vegetation	
Hymenoptera	Braconidae (1)	parasitic wasps	Terrestrial	AR, CO, KY, TN, TX, WY, BC
	Ichneumonidae (4)	parasitic wasps	Terrestrial	
	Formicidae (10)	ants	Terrestrial	
	Vespidae (1)	wasps	Terrestrial	
	Megachilidae (5)	leafcutter bees	Terrestrial	
	Unknown family (4)			
Unknown affiliation (162)				

dants. The present-day habitats of the orders and genera are indicated in Table 1. From this information we can speculate that the area surrounding the lake could have been a meadow near an upland mixed deciduous/conifer forest. The presence of certain terrestrial Diptera (especially Bibionidae) and Coleoptera in the rocks suggests nearshore deposition (Wilson, 1980), but some Hymenoptera and certain Diptera are strong fliers and could travel far from shore. The fossil plants also help shape our concept of the environment (Wolfe and Wehr, 1991). To date, however, there is little information about meadow plants that were probably present at this locality. Combining continuing study of the insect and plant fossils (including pollen) with examination of the geologic setting will improve our understanding of the Eocene environment and of insect evolution.

References Cited

Cockerell, T. D. A., 1915, Miocene fossil insects: Academy of Natural Science, Philadelphia, Proceedings No. 66, p. 634-648.

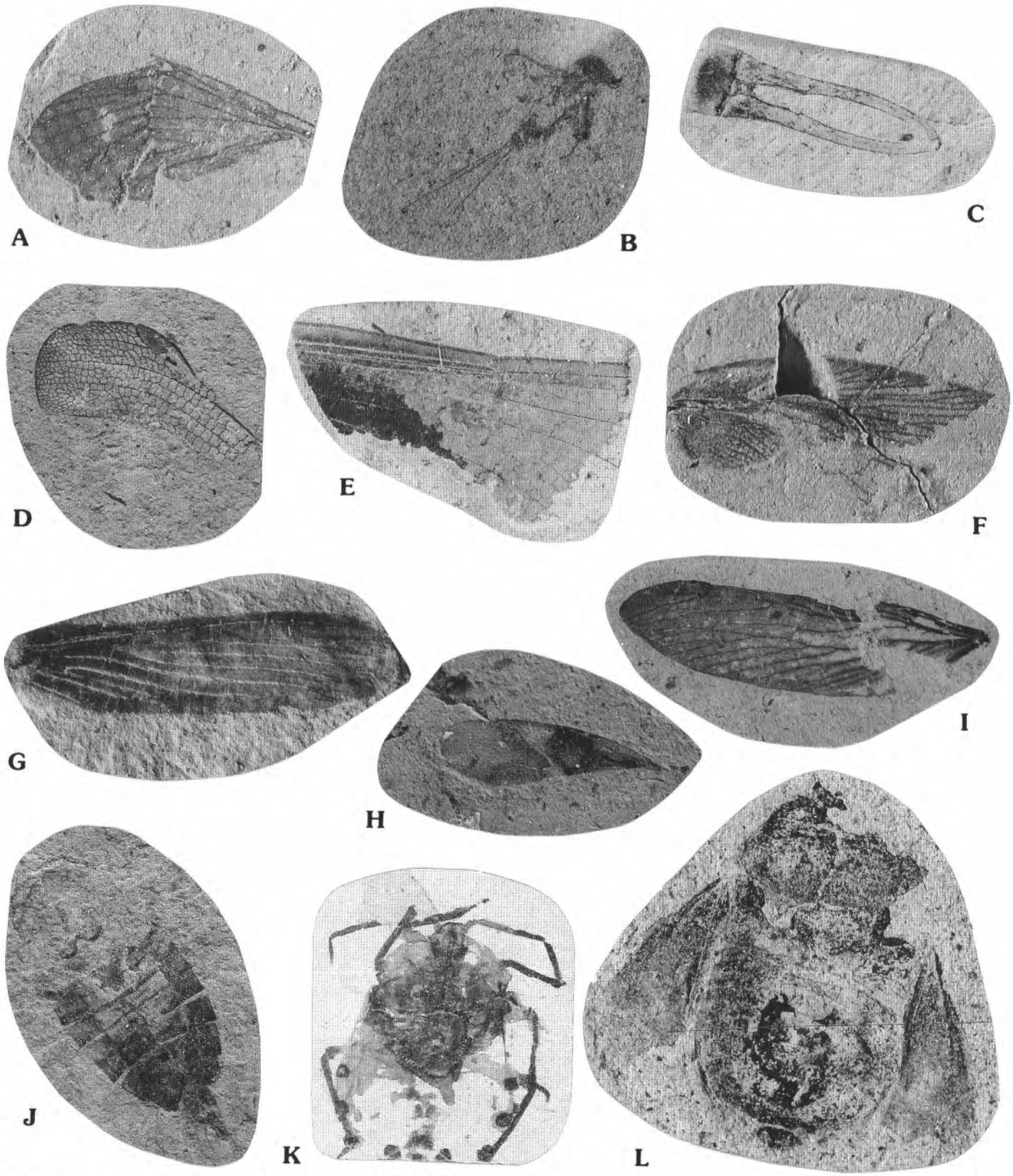


Plate 1. Wings, body parts, and bodies of insects in the middle Eocene lakebed strata at Republic, Washington; numbers are specimen catalog numbers for the Thomas Burke Memorial Washington State Museum collection at the University of Washington (UWBM) or the paleontological collection at St. Cloud State University (SCSU). **A**,**B**, Ephemeropterans; A, wing, UWBM 57198, x3.4; B, Family Heptageniidae, immature, UWBM 57158, x3.0. **C**, Dermaptera (Family Forficulidae), anal forceps of the female, UWBM 57160, x5.7. **D**,**E**, Odonatan wings; D, Family Zacallitidae, *Zacallites*(?) sp., apical end of wing, UWBM 72289, x4.8; E, basal portion of wing, SCSU 7B-16, x4.4. **F**,**G**, Orthopteran wings; F, Family Blattoidea, forewing, UWBM 72290, x4.2; G, forewing, SCSU 8-1, x4.7. **H**, Isopteran forewing, SCSU 7B-2, x4.5. **I–L**, Hemipterans; I, forewing, UWBM 72291, x5.0; J, Family Belostomatidae or Pentatomidae, abdomen, UWBM 56326, x2.2; K, Family Pentatomidae, dorsal view, UWBM 57176, x2.3; L, Family Pentatomidae, dorsal view, (Stonerose Interpretive Center collection), x4.6.

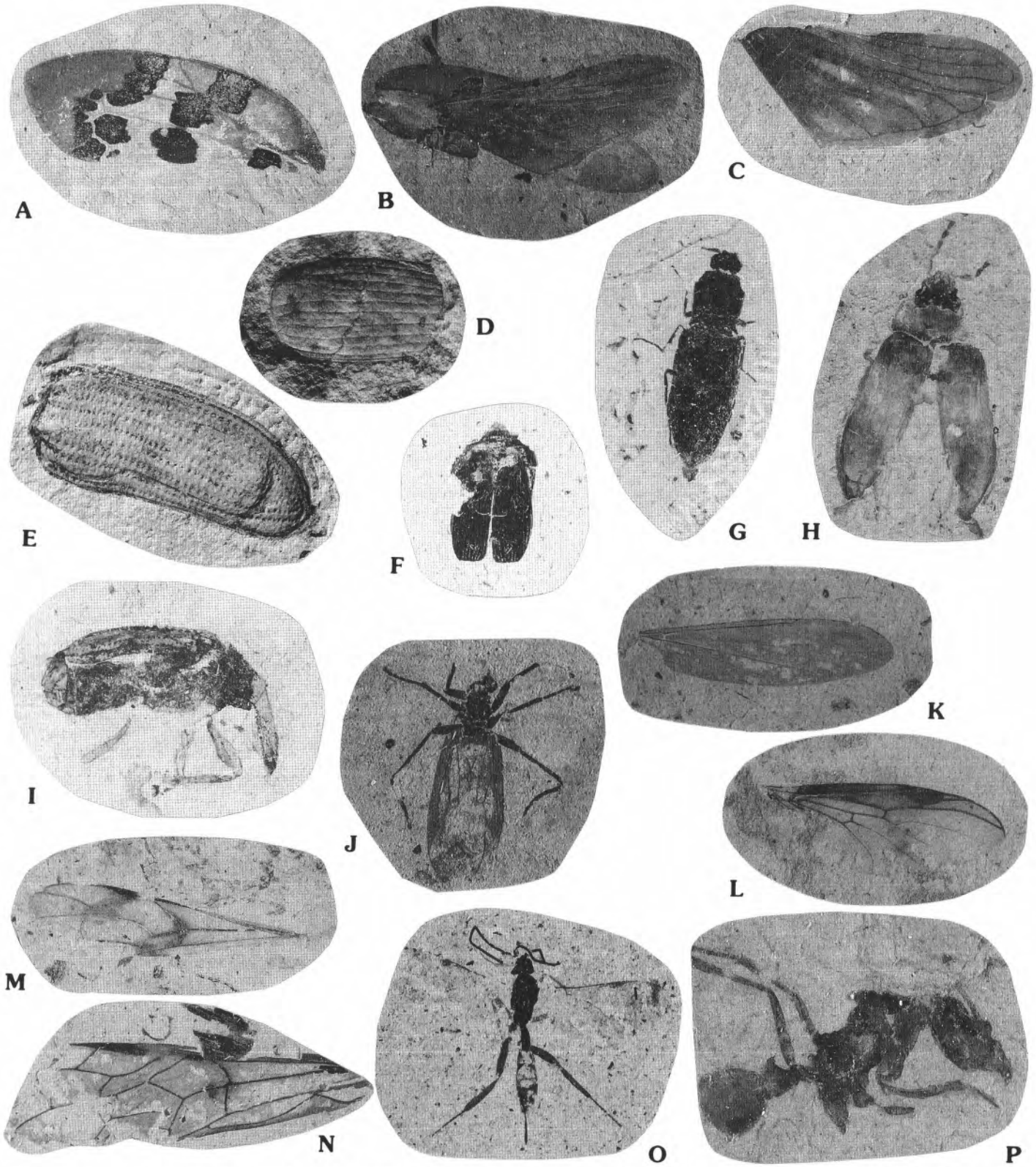


Plate 2. Wings and bodies of insects from the middle Eocene lakebed strata at Republic, Washington; numbers are specimen catalog numbers for the Thomas Burke Memorial Washington State Museum collection at the University of Washington (UWBM) or the paleontological collection at St. Cloud State University (SCSU). **A–C**, Homopterans (Family Cercopidae); A, forewing, UWBM 72296, x2.0; B, *Aphrophora* sp. wings, UWBM 57317, x1.8; C, *Aphrophora* sp. hindwing, UWBM 72297, x2.0. **D,E**, Coleopteran (Family Carabidae) forewings; D, SCSU 7B-15, x7.3; E, UWBM 57104, x4.2. **F–H**, Coleopteran bodies, dorsal views; F, UWBM 54811A, x4.9; G, (Family Elateridae), UWBM 57095, x3.6 [specimen from Princeton, B.C.]; H, UWBM 54097, x3.6. **I**, Coleopteran (Family Curculionidae) body, side view, UWBM 57096, x3.6. **J**, Dipteran (Family Bibionidae) body, dorsal view, UWBM 56684A, x3.4. **K,L**, Dipteran forewings; K, (Family Tipulidae), SCSU 7B-59, x4.4; L, (Family Bibionidae), SCSU loc. 7B, x4.2. **M,N**, Hymenopteran forewings; M, (Family Ichneumonidae), UWBM 57122, x3.7; N, unidentified family, UWBM 54840, x3.7. **O,P**, Hymenopteran bodies; O, (Family Braconidae), UWBM 57116, x4.5; P, (Family Formicidae) (Stonerose Interpretive Center collection NS-BR-2), x4.5.

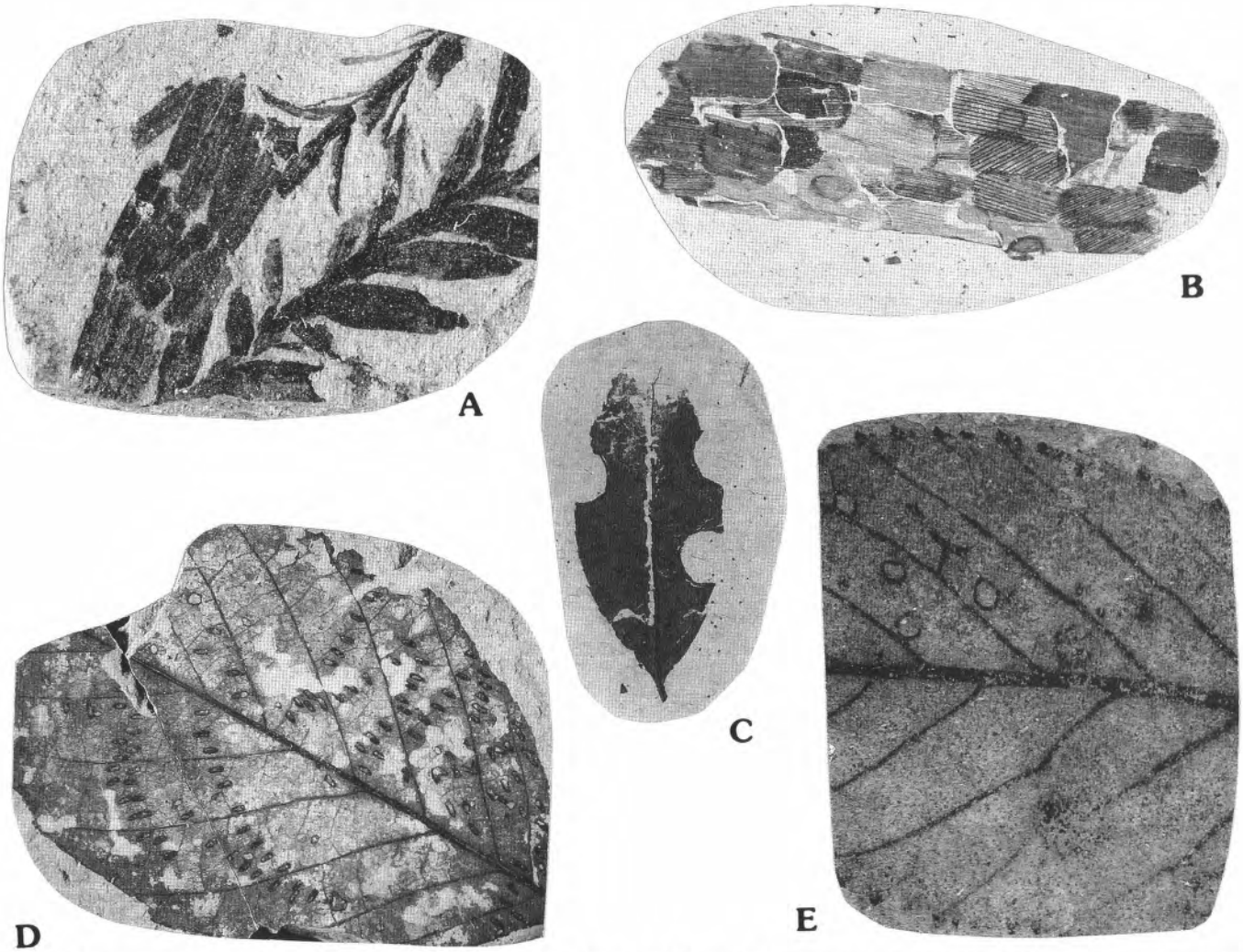


Plate 3. Indirect evidence of insects in the middle Eocene lakebed strata at Republic, Washington; numbers are specimen catalog numbers for the Thomas Burke Memorial Washington State Museum collection at the University of Washington (UWBM) or the paleontological collection at St. Cloud State University (SCSU). **A**,**B**, Cases of Trichoptera (Family Phryganeidae); A, UWBM 57163, x4.1; B, UWBM 55204, x2.3. **C**, Eggs of *Altica* sp. (Coleoptera, Chrysomelidae) on an alder leaf, UWBM 57187, x1.3. **D**, Leafcutter bee (Hymenoptera, Megachilidae) damage to a *Prunus* leaf, UWBM 57529, x0.9. **E**, Insect damage to a leaf, SCSU FR-1, x1.0.

Joseph, N. L., 1986, Eocene flora and fauna unearthed at Republic: Washington Geologic Newsletter, v. 14, no. 4, p. 3-5.

Kevan, D. K. McE.; Wighton, D. C., 1983, Further observations on North American Tertiary orthopterids (Insecta: Grylloptera): Canadian Journal of Earth Sciences, v. 20, no. 2, p. 217-224.

Lewis, S. E., 1989, Eocene insect localities in the U.S. and Canada: Occasional Papers in Paleobiology at St. Cloud State University, v. 3, no. 2, p. 1-38.

Lewis, S. E.; Carroll, M. A., 1991, Coleopterous egg deposition on alder leaves from the Klondike Mountain Formation (middle Eocene), northeastern Washington: Journal of Paleontology, v. 65, no. 2, p. 334-335.

Lewis, S. E.; Heikes, P. M., 1991, A catalog of fossil insect sites from the Tertiary of the United States: Occasional Papers in Paleobiology at St. Cloud State University, v. 5, no. 1, 487 p.

Scudder, S. H., 1890, The Tertiary insects of North America: U.S. Geological Survey of the Territories, v. 13, 733 p.

Wilson, M. V. H., 1977, New records of insect families from the freshwater middle Eocene of British Columbia: Canadian Journal of Earth Sciences, v. 14, no. 5, p. 1139-1155.

Wilson, M. V. H., 1980, Eocene lake environments—Depth and distance-from-shore variation in fish, insect, and plant assemblages: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 32, p. 21-44.

Wolfe, J. A.; Wehr, W. C., 1991, Significance of the Eocene fossil plants at Republic, Washington: Washington Geology, v. 19, no. 3, p. 18-24.

Note: Fossils are a nonrenewable resource. Searching for fossils at the Republic site is permitted from 10:00 a.m.–5:00 p.m., Tuesday–Saturday, and from 10:00 a.m.–4:00 p.m., Sundays until September 15, after which no digging will be allowed on Sundays. Register with the Stonerose Interpretive Center (next to the city park) before searching, and bring your specimens to the center. If you find a particularly fine or new fossil, the center will ask you to leave it with them to assist scientists with their on-going work. Please do not look for fossils in the marked areas set aside for research. ■

Reclamation of Sand and Gravel Mines

by David K. Norman and William S. Lingley, Jr.

INTRODUCTION

The Surface Mining Act (Chapter 78.44 RCW) sets forth minimum allowable standards for mine reclamation in Washington. However, miners are often at a loss for guidance when it comes to restoration. There is little published information and even less scientific research on methods of achieving effective gravel-pit reclamation. This article is intended to introduce sand and gravel miners to various reclamation options.

Reclamation objectives are similar for most gravel mines. Short-term goals are maintaining air and water quality and reducing aesthetic impacts during mining; these can be accomplished chiefly by minimizing the disturbed area. The main long-term objectives are to return gravel pits to a stable, usable condition and to produce an area that blends with its surroundings.

These objectives are accomplished by sculpting the mined surface and establishing a pioneer vegetative community that will ultimately produce a new multi-layer soil and a self-sustaining ecosystem. This objective can be realized if the miner adopts a stewardship approach, like that of a farmer planting crops for harvest. There are many ways to accomplish these goals, and each site presents opportunities for creative responses to the regulations. And there are many good examples of reclamation in Washington mines.

RECLAMATION STRATEGIES

RCW 78.44.080 identifies subsequent use as a criterion for guiding the reclamation scheme. For example, restoring sinuous, natural-appearing topography is necessary for mines in scenic areas. When planning mines in deposits that overlie aquifers, the subsequent use cannot preclude restoration of dense vegetation or impermeable top seals that will protect the aquifer. Reclamation literature, however, makes numerous references to subsequent uses that are uncommon in a competitive market, such as golf courses.

Three strategies are generally used in surface-mine reclamation:

(1) Progressive or continuous reclamation, in which minerals are removed and overburden is immediately replaced; this is the method used in strip mining minerals such as coal

(2) Reclamation after all resources have been depleted from the entire mine

(3) Segmental reclamation, or reclamation following depletion of minerals in a sector of the mine.

The legislature recognized segmental reclamation as the strategy of choice for most Washington sand and gravel mines and adopted it in 1970 as part of the Surface Mining Act.

Sand and gravel miners rightly point out that progressively reclaiming land that overlies known mineral resources can be wasteful. Progressive reclamation is perceived by the public as the preferred technique. However, soils that overlie most sand and gravel deposits are thin and render this technique impracticable or impossible for those operations that must blend different sand and gravel sizes from various parts of the mine site in order to achieve product specifications. Untimely interim reclamation results in: (1) disturbing more land per unit of mineral produced and (2) diminished final reclamation quality because more soil is moved more often. On the other hand, postponing reclamation until all resources are depleted does nothing to mitigate short-term environmental impacts on air and water and nuisances to neighboring residences.

Advantages of segmental reclamation over reclamation after completion of all operations are: (1) it generally costs less because less material is moved and (2) it establishes final slope angles and shapes in the process of excavation rather than as a separate operation. Segmental reclamation uses equipment while it is on site. It also reduces loss of clay and silt, which are critical for retaining moisture and nutrients essential for vegetation. Segmental reclamation enhances the potential for establishing a self-sustaining soil/plant ecosystem. Restoration of chemical, physical, and biological processes is less expensive when reclamation is started as soon as possible and spread over the life of the mine.

Segmental reclamation works best in homogenous deposits where mining proceeds in increments. A typical segment might comprise 600 linear feet of working face and 6 acres. Segments will be larger in heterogeneous deposits (for example, fluvial deposits), where blending minerals from many places in the mine is required. Prior to mining, topsoil in the first segment is strategically stockpiled to minimize handling. When the sand and gravel have been removed from the first segment and the slopes have been reshaped according to the reclamation plan, topsoil from the first and second segments is spread on the first segment's surface. Prompt planting with grasses, legumes, and nitrogen-fixing trees will quickly produce a cover that reduces erosion, retains moisture, and reduces the heat on the slope surface. Revegetation of the floor of the first segment does not occur until the area is no longer needed for mineral processing or maneuvering trucks. Immediately prior to planting, the pit floor is plowed or ripped because most plants cannot grow in soils that have been over-compacted by heavy machinery.

RECLAMATION PLANS

An operating and reclamation plan can be thought of as both a financial planning document and a contract that defines the topography and vegetation of the site after reclamation is complete. This plan describes the strategy to achieve acceptable reclamation at the lowest possible cost by establishing an economic limit of gravel production for each site. It also identifies and addresses mitigation of potential environmental impacts, such as gullying of impermeable clays or sands, for which the operator is liable; establishes a segmental sequence of mining and reclamation that will avoid unnecessary earth moving; and identifies appropriate equipment.

A good operating and reclamation plan should be simple, practical, and easy to implement. The plan should be flexible and take into account the potential for unanticipated changes in the geology and market that will affect reclamation. The plan should make provisions for quality reclamation even if

mining to depletion never occurs. Managers and senior equipment operators must be familiar with the reclamation obligations to which the permit holder has committed.

A typical plan might include:

- A description of the ground-water hydrology and details of how the site will be mined (that is, wet or dry)
- Existing topography
- Subsequent use of the land, appropriate for the location of the mine
- Sequence of topsoil stripping, storing, and replacement on mined segments
- Designation of overburden storage areas beyond the limit of mining but positioned for the shortest possible downhill transport during reclamation
- Direction and sequence of excavation that will result in reclamation as soon as possible after completing mining on any segment and within the constraints of economically efficient mining
- Location of waste rock piles and how they will be reclaimed and stabilized
- Final grades and shapes of the pit walls and floor to incorporate sinuous contours and effective drainage
- Permanent drainage and water-control systems
- Schedule of planting to assure plant survival
- Specifications for ground-cover plants to minimize erosion and establish conditions that will increase the survival rates of trees
- Tree-planting specifications and schedules to make use of conditions established by a healthy ground cover.
- Locations of trees to stabilize the site and generate a new humic layer
- Other information pertaining to the permit and required by statute.

Figure 1 shows maps and cross sections from a typical operating and reclamation plan for a sand and gravel mine. The mine will be excavated initially as a dry site, but mining to greater depths will eventually penetrate the water table and result in a permanent lake and associated wetlands. The operational portion of the plan is used to identify excavation areas, processing facilities, roads, utilities, stockpiles, water-control systems, visual screens, berms, and areas to be left undisturbed. Maps and cross sections display information such as slope angle and shape, revegetation plans, and final drainage. In Figure 1a, special attention has been given to moving topsoil and overburden. Narrative explanations (not included in Fig. 1) normally accompany the maps and cross sections to provide additional details of the operating and reclamation plan.

GENERAL GUIDELINES

Sand and gravel pits in western Washington are fairly easy to reclaim because the moist climate increases production of the clay component in soil and provides abundant precipitation for pioneer plants. Mined areas in eastern Washington are more difficult to reclaim because that region is drier and temperatures are more extreme. In addition, many soils contain fewer nutrients and are coarser. Wind in eastern Washington readily removes clay and silt from exposed soil. Therefore, successful revegetation in the eastern part of the state is more dependent on proper plant selection, appropriate timing of planting, adequate fertilization, presence of organic matter, and, commonly, irrigation.

SITE PREPARATION

Removal of Vegetation

In a well-planned operation, vegetation is removed sequentially from areas to be mined. Vegetation is preserved where necessary to screen the site and to limit turbid water discharge from areas that will be disturbed.

Vegetation that is tilled into the replaced soil can increase humus. Woody material can be chipped and used as mulch or to add organic matter to the soil. Some of the trees and shrubs that have been cleared prior to mining can be set below the water table to form artificial "reefs" to provide habitat in new lakes or wetlands or placed in brush piles above ground to provide cover for wildlife.

Burying woody debris is allowed only if permitted by the county health district. In general, burial of any compressible material, even if allowed by the health district, should only be done in areas that will not be used for construction. As the debris rots, the pile compacts, and buildings placed on these piles may be damaged as the ground settles.

Bushes and small trees, together with some surrounding soil, can be scooped up and then transplanted to mined-out segments by using backhoes or front-end loaders. This technique is a cost-effective means of establishing a natural appearance in reclaimed segments, introducing seed trees, and providing screening from neighbors. These plants are already adapted to the area. Moving both soil and plant protects minute rootlets and micro-organisms that are important to plant propagation. Additionally, this soil may contain seeds or shoots of other vegetation; this facilitates spreading the flora across nearby areas.

Removing, Storing, and Replacing Topsoil and Subsoils

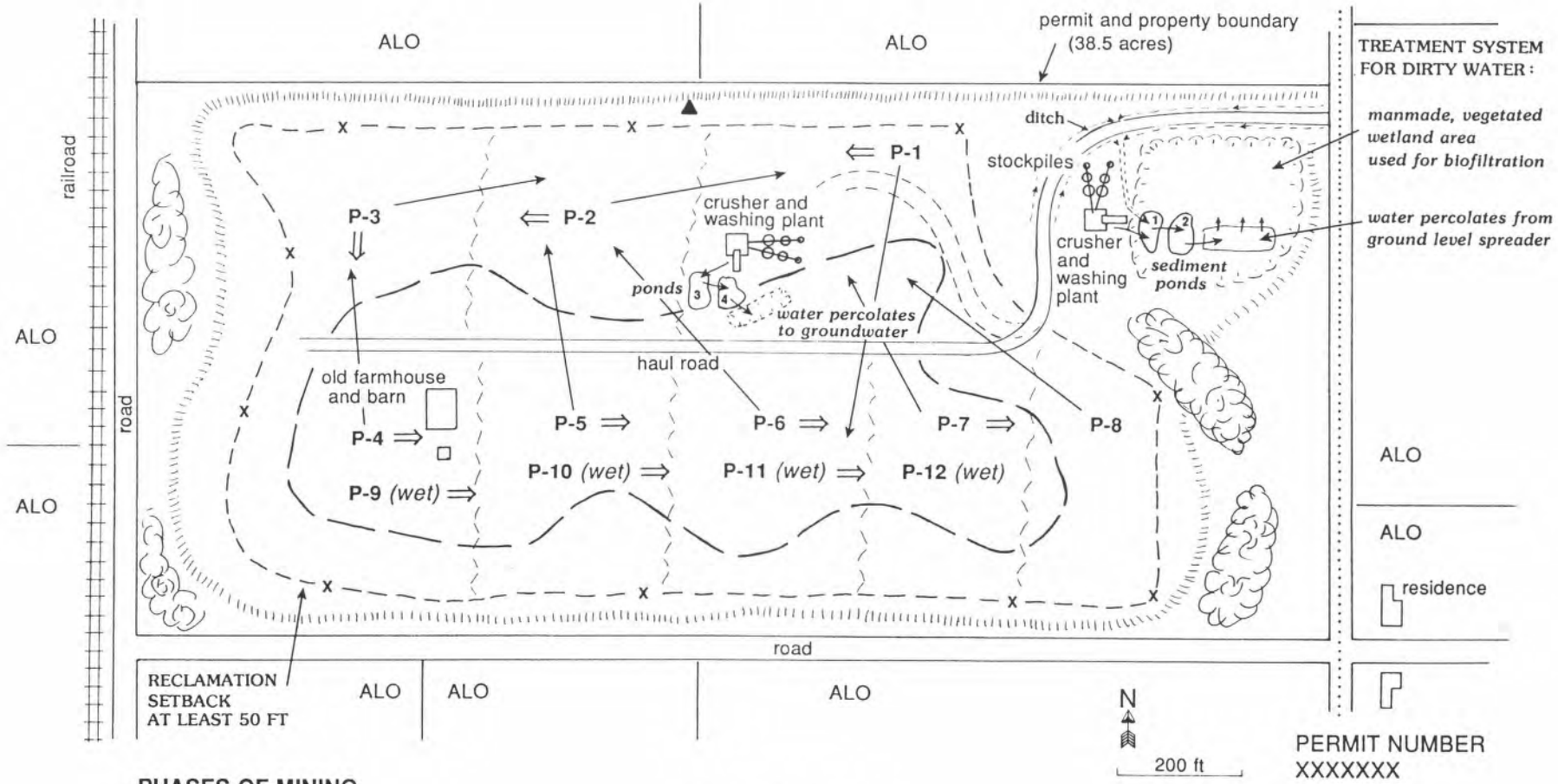
Topsoil can be identified by its dark color and humic content. It also has high water-retention capacity. Subsoils commonly contain fewer nutrients, but abundant clay in subsoils can adsorb moisture and nutrients. Furthermore, subsoils may act as a top seal that protects underlying aquifers.

Because topsoil is essential to successful reclamation, it should not be sold as a by-product of sand and gravel mining unless specific authority has been granted in the permit documents. Where there is insufficient topsoil for reclamation, clay-rich subsoils can be combined with wood waste to manufacture a topsoil substitute.

As mining proceeds, topsoil, subsoil, and other overburden not used immediately in reclamation should be stripped and stockpiled separately and revegetated to avoid erosion. Loss of fungi, rootlets, and micro-organisms in topsoil results from both moving and storing topsoil. Topsoil stored longer than 5 years is severely degraded. Soil structure is damaged if the soil is moved when too wet, and soil porosity is reduced by compaction. It is best to plan to move the soil only once, which also keeps operating costs low.

Topsoil should be replaced on slopes as soon as possible after restoration of topography. The less equipment moving over soils, the better: use of heavy earth-moving equipment, rubber-wheeled vehicles, and narrow tracks should be avoided during re-application so that soils are not compacted.

A common problem in re-applying topsoil and subsoil is spreading them too thickly initially so that little is left for remaining areas. A combination of not less than 8 inches of topsoil and 3 feet of subsoil is optimal. If topsoil is not



PHASES OF MINING

EXPLANATION

- edge of excavation
- edge of water in excavation
- berm - 20 ft high - planted with grasses, legumes, and shore pine to screen operation (berm removed only after mining is complete on entire project)
- ▲ permanent concrete monument for reference point
- original screening trees preserved
- gas pipeline
- ALO adjacent landowner
- ← indicates direction of topsoil and overburden stripping and replacement for reclamation
- P-3 ⇒ indicates phase and direction of mining
- x stakes at excavation limit (steel pipe 1.5 in. diameter, 4 ft above grade)

Figure 1a. Map for an operating and reclamation plan that shows the sequence of segments to be mined (counterclockwise from the northeast in this instance), as well as details of soil placement, screening, and drainage. This site is mined first as a dry site, but as mining proceeds into the southern segments, the water table is penetrated. The site will accommodate a small office complex and wildlife habitat when it has been reclaimed.

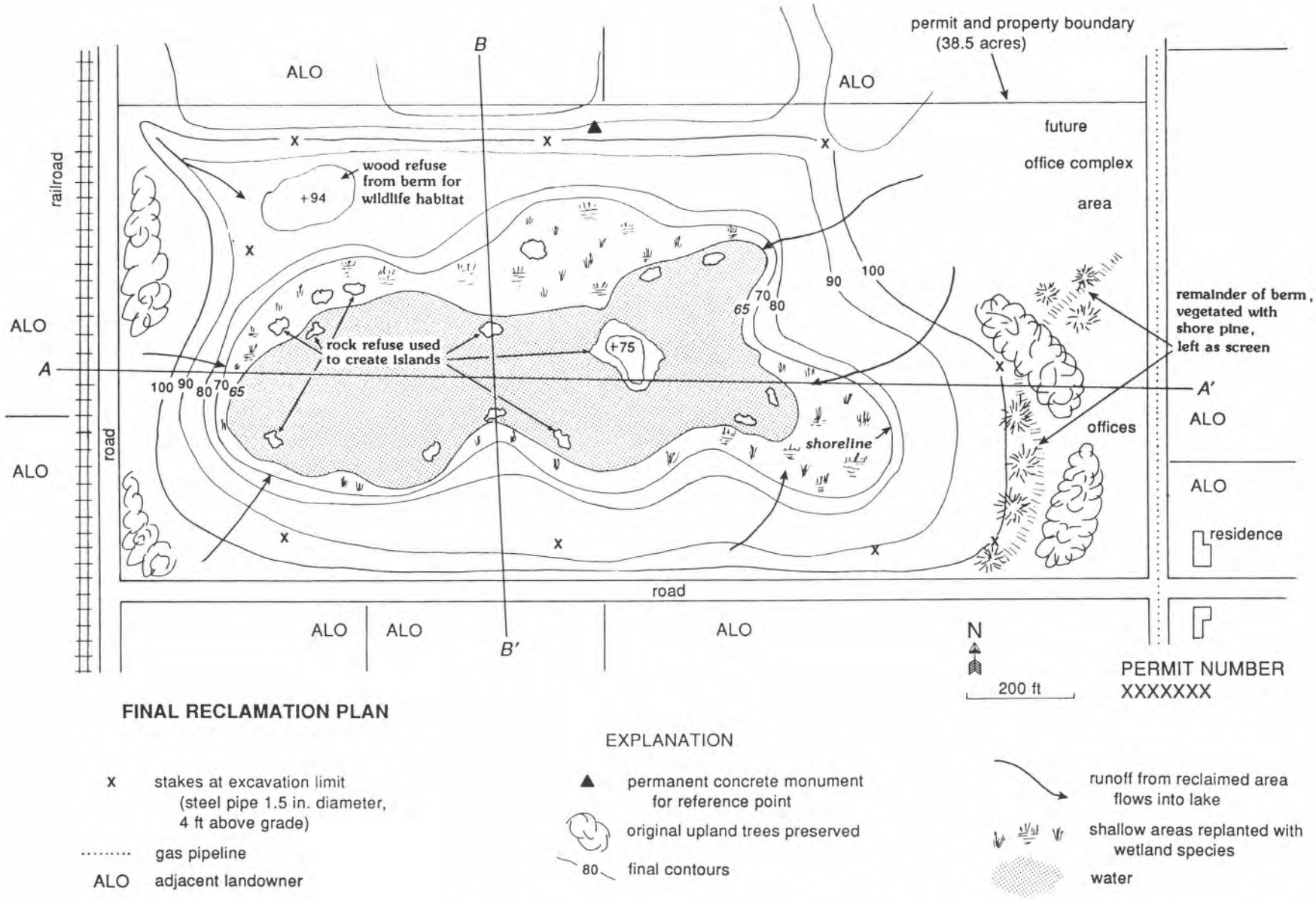


Figure 1b. Contour map of the site shown in Figure 1a as it will appear after reclamation. Cross sections A–A′ and B–B′ are shown in Figure 1c.

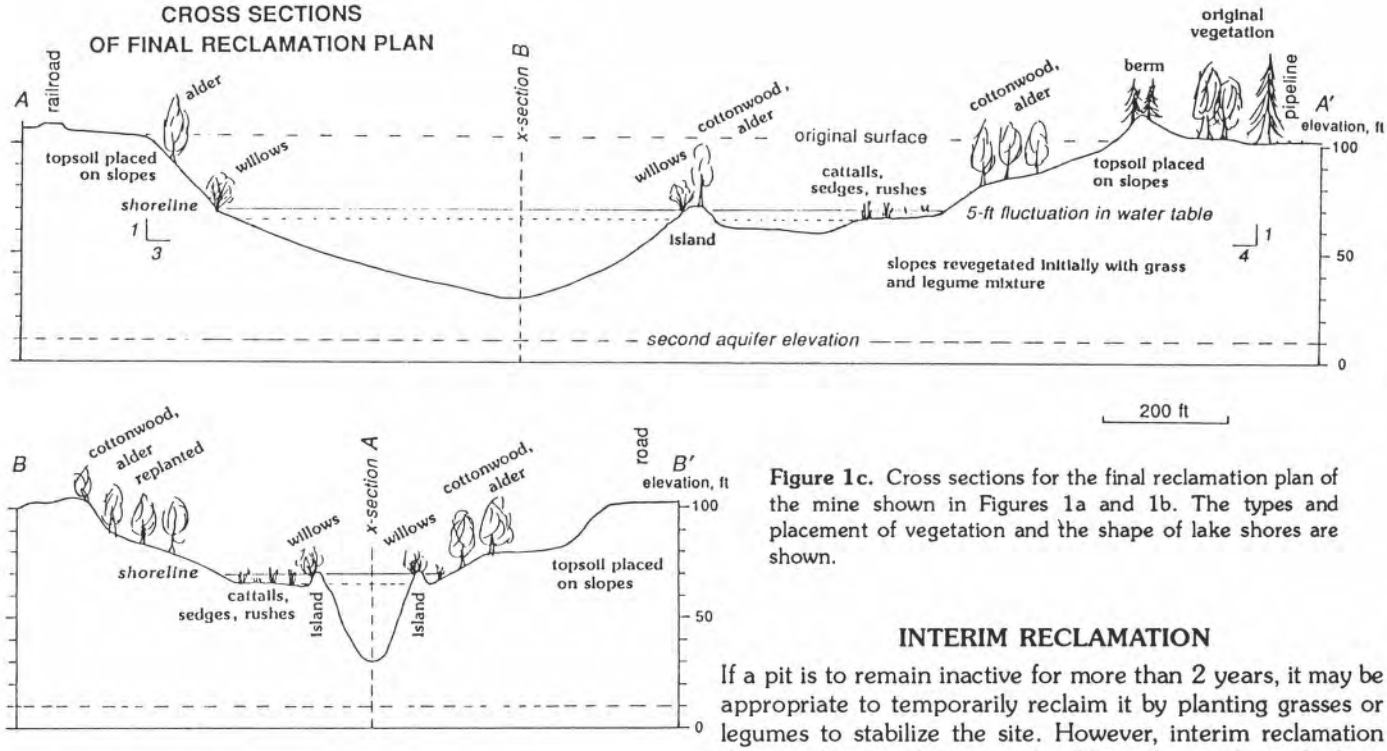


Figure 1c. Cross sections for the final reclamation plan of the mine shown in Figures 1a and 1b. The types and placement of vegetation and the shape of lake shores are shown.

plentiful, its application should be restricted to low areas or excavated depressions that will conserve soil, retain moisture, and catch wind-blown pioneer seeds. These are also ideal sites for planting trees.

BUFFERS, SETBACKS, AND SCREENS

Buffer zones and reclamation setbacks are necessary at many mines because they provide visual, noise, and discharge screening. Although generally less effective than buffer zones, which rely on distance for their effectiveness, narrower buffers for screening can be created with vegetation, walls, fences, or berms.

Natural buffer areas should remain undisturbed during the life of the mine. Keeping equipment and stockpiled materials out of buffer areas will help to preserve them; flagging, fences, or monuments will alert operators to areas to be avoided in mining or reclamation. If vegetation is present on slopes that might be unstable if bare, those plants should be protected. Activity near trees and shrubs should be kept outside the area below the longest branches (or drip line).

If the cut-and-fill method is to be used to restore slopes, a setback from the property boundary that will assure sufficient material for reclamation is almost always necessary. For example, on a vertical mined face, if a 3 feet horizontal to 1 foot vertical (3H:1V, 33%, or 18 degree) final slope is required, a setback 1.5 times the depth of excavation will be necessary to provide material—that is, a 40-foot-high slope will require a 60-foot setback to provide the necessary volume of material to create the desired slope when mining is completed. On gentler slopes, less material will need to be moved to achieve the reclaimed slope.

Setbacks from streams are essential and should be at least 200 feet wide. No part of that width should be on the 100-year floodplain unless a shoreline permit has been issued.

INTERIM RECLAMATION

If a pit is to remain inactive for more than 2 years, it may be appropriate to temporarily reclaim it by planting grasses or legumes to stabilize the site. However, interim reclamation that involves earthmoving should not be performed where topsoil necessary for final reclamation is in short supply. About 15 percent of this soil is lost each time it is moved. Blocking roads and building fences can help protect inactive mines by reducing access and unauthorized activities such as garbage dumping and off-road recreation.

SHAPING THE RECLAIMED PIT

A key element in restoring topography is creating slopes that blend with the surrounding landforms. The goal is to establish rough slopes that are curved in plan and section (Fig. 2). Rectilinear slopes are inappropriate for reclamation because they are prone to sheet erosion and gullying and because they look unnatural. Sinuous slopes can be formed either by mining to the prescribed angles or by using the cut-and-fill method. New drainages should be established, and contours must tie smoothly with contiguous offsite topography.

Rough, rounded topography cannot be achieved without bringing bulldozer operators into the final reclamation planning process because uninformed operators normally create the traditional straight-planar topography (by "grading").

The terrain at a reclaimed site should consist entirely of stable slopes. A rule of thumb is that slopes are unstable if pioneer plants cannot establish themselves naturally or if the slopes ravel. In general, sand and gravel are stable and can sustain vegetation at slopes of 3H:1V. To vary the topography, a few locally steeper areas (1.5H:1V) may be created. However, these areas will be difficult to revegetate and will be unstable unless the substrate has a high enough clay content to retain moisture or is covered with topsoil.

Bare or steep slopes greatly increase the potential for erosion. Long steep slopes produce more and faster runoff and allow less infiltration than short, gentle slopes.

Some guidelines for slope reclamation are:

- Steep slopes (such as 3H:1V) should be kept shorter than 75 feet by curved terracing and berming.

- Tracked equipment should be run up and down a slope, rather than across, to increase slope roughness, which in turn will intercept more runoff and reduce its velocity, trap seeds, and speed revegetation. (Older bulldozers are generally unable to back up sand and gravel slopes steeper than 3H:1V.)
- Reclaimed working faces should be revegetated immediately following creation of the slope to minimize erosion.
- If the site is to be dry after mining, then pit floors should be graded to a slope of 2 to 5 percent to promote drainage.
- Mounds and hills can be left on the flatter areas of pit floors to vary the topography.

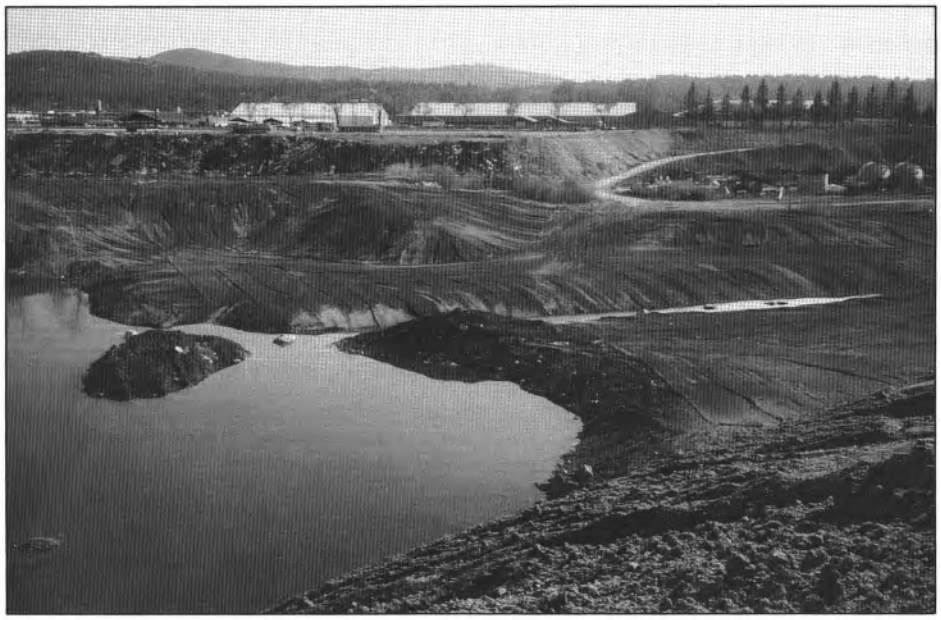


Figure 2. Moving earth and shaping the mined surface are important steps in reclamation. Shown is the Central Pre-Mix Yardley pit, where the central part of the pit is being shaped with gentle contours, canals, and islands. Subsequent uses of this pit are a heavy industrial area (concrete products) and a lake and wetland area for wildlife. (Photo by Mark Murphy, Central Pre-Mix)

Surface-water Drainage

Planning drainage for the site is critical. During operations, water should be passed through vegetated areas or sediment retention systems to slow runoff and filter or settle muddy water. Following mining, dry retention ponds are good sources of clay for other parts of the mine. Clay slurries from these ponds have been pumped onto barren gravel slopes at the Steilacoom mine to provide a clay-rich substrate for plants.

During mining, water should be diverted around slopes to prevent both erosion and mixing turbid with clear water. Diverted water should tie into the natural drainage. Dikes, ditches, or a combination of these structures divert runoff from the working face. For short slopes, placing a diversion at the slope top works well. For longer slopes, diversions can be placed at intervals to effectively reduce slope length.

Manmade drainages should be sinuous, have a low gradient, and be protected by riprap or vegetation or both. They should be designed to control the 100-year 24-hour precipitation event indicated on the maps in Miller and others (1973). If ponds are to be left, then drainage can be directed to the ponds. Outlets from ponds must be identified and carefully protected from erosion, which could cause catastrophic breaching of the pond. Guidelines for shaping reclaimed sites that extend below the water table are presented under "Subsequent Land Uses".

Approval from the Department of Fisheries or the Department of Wildlife is required prior to diverting streams. See Norman (1992) for a discussion of the jurisdictions and responsibilities of other agencies.

REVEGETATION OF THE SITE

In the past, many operators relied solely on natural revegetation. However, aggressive revegetation quickly improves the appearance of a site, stabilizes the soil, reduces erosion, and eliminates turbid offsite water discharge. It can also result in reduction of the State security bond for reclamation. Revegetation early in the reclamation process ensures that plants are thriving when the mine is closed.

Mined sites generally present harsh conditions that hamper re-establishing vegetation. Nevertheless, much can be done in the planning stages to increase the chances for successful seeding and planting. Selection of the right seeds and plants for the site, good seedbed preparation, timing of planting, and conscientious maintenance are important.

A useful publication for selecting plants is The Washington Interagency Guide for Conservation and Forage Plantings (Washington State University Cooperative Extension, 1983; available at minimal cost). Local nurseries may be able to provide appropriate plants and seeds. A directory of Pacific Northwest native plant suppliers can be obtained from Hortus Northwest (503/266-7968) in Canby, OR, the Department of Natural Resources, or the local phone book. (See also Shank, 1990.) The Soil Conservation Service and county extension agents may also be sources of information.

Revegetation with grass and legumes should occur during the first appropriate season after slope shaping and replacement of topsoil. In this way, erosion by wind and water is minimized and the possibility of landslides or other slope failures is diminished. However, vegetation cannot be expected to control erosion or prevent soil slippage on unstable slopes. The 1.5H:1V slopes allowed under the surface mining statute (RCW 78.44.090) have failed by landslide even where covered by dense growths of Scotch broom.

Earthwork, usually completed during the summer, should be followed by aggressive revegetation in the fall. First plantings should be ground cover consisting of a mixture of grasses and legumes that are quick to establish. Successful revegetation is often dependent on the weather. Spring revegetation is usually successful only if the spring and summer are cool and wet. Fall revegetation is normally successful if the season is wet and warm. Ground cover should be supplemented with pioneer trees and shrubs. Late winter is often the best time to

plant shrubs and trees. Miners should be prepared to irrigate young plants; however, long-term irrigation is neither cost effective nor ecologically sound.

Whenever possible, native species should be used for replanting. These plants are adapted to local conditions, and survival rates are high. Native species are less likely to require irrigation, which is a large maintenance burden. Scotch broom and gorse are widespread pioneer plants that fix nitrogen, but these are not native and are considered undesirable noxious weeds. If they are already established at a mine site, it is appropriate to leave them until the site is stabilized. (Unfortunately, many weeds currently targeted by weed control agencies are superior for reclamation purposes.) Clearing small areas and planting trees, if conditions permit, begins the process of eliminating Scotch broom or gorse while maintaining site stability and minimizing erosion.

Figure 3. Nitrogen-fixing species such as red alder, clover, and Scotch broom are useful in reclamation because soils in many mined areas are deficient in nitrogen. [Scotch broom should gradually be eliminated from the site.] Initial attempts to revegetate this area with grasses and Douglas fir were unsuccessful. A stand of red alder just beyond the area of this photo was left to act as a seed source for the young trees, shown here with mine operator Milt Emerick. The nitrogen added to the soil by these plants improves the soil for later plantings.

A trial-and-error approach to revegetation relying on natural precipitation and hardier natural pioneer species (such as alder) is generally less expensive, uses less labor, and is more effective than waiting until mining is complete to plant the entire site with commercial plants. Segmental mining results in fairly small areas on which to begin this process. Test plots can be used to determine which species will be successful. Areas in which plants fail to establish can be reseeded with more appropriate vegetation.

It is tempting, particularly with trees, to plant only climax species (for example, Douglas fir) even if the ground is not fully prepared. However, natural communities develop slowly through a succession from pioneer species to climax, each phase preparing the ground for the next. Mimicking this progression during reclamation is impractical, but planning a phased succession for both ground cover and trees will establish a good climax mix.

Grassland development can start with either a quick pioneer soil builder under a developing woodland or a climax flora for grazing. Similarly, many pioneer trees will act as a quick-growing nursery for evergreens and other trees that mature slowly and do not grow well in fresh ground or open areas. Nitrogen-fixing species (herbaceous legumes such as clover and lupine, and trees such as black locust, Russian olive, and alder) play a crucial role in the soil building and development stages (Fig. 3). (See Table 1).

Generally, establishing widespread healthy vegetation takes several seasons. Follow-up evaluations may be necessary to monitor progress and to determine why plants did not thrive. If vegetation is evenly but sparsely distributed over the entire area, minimal reseeding and fertilization is needed. However, if vegetative cover is inadequate to prevent rill erosion, the eroded areas should be regraded, reseeded, and fertilized in accordance with the soil test results. If large areas remain bare after 1 year, the choice of plants and fertilizer should be re-evaluated and the process restarted.

Tree and Shrub Planting

In addition to their slope stability, sediment control, and visual screening values, trees and shrubs reduce the rectilinear appearance of most sand and gravel mines. They also provide natural beauty and wildlife benefits; for these uses they are more effective when planted in clumps or groups. Suitable species are listed in Table 1.

Some guidelines to help assure successful planting are:

- Trees and shrubs do best if planted in topsoil.
- If no topsoil is available, trees or shrubs can be established in subsoil amended with generous amounts of organic matter.
- When planting trees and shrubs, make sure roots are not twisted, exposed, or placed on boulders and that there are no large air pockets in the soil.
- Mulches of straw, leaves, grasses, or wood chips should be piled around the base of trees and shrubs.
- Competing vegetation, if significant, should be removed from the area where trees or shrubs are to be placed.
- High-quality stock should be used. Normally, 1- or 2-year-old deciduous seedlings and 3- or 4-year-old conifer transplants are adequate.
- Planting should be done while trees and shrubs are dormant, generally from early November to late March.
- Stock should be properly handled, including being kept cool and moist and planted as soon as possible.

A cost-efficient method of establishing trees is to plant willow, poplar, evergreen, or alder shoots that can be taken from ditches along many roads. Branches cut from willows will take root in wet sites, especially if the ends of the cuttings are coated with rooting hormones.

Table 1. Some recommended trees for reclamation in western and eastern Washington (adapted from Coppin and Bradshaw, 1982); P, pioneer species; Cl, climax species; N, fixes nitrogen; D, dry sites; M, moist sites; W, wet sites; Fl, tolerates flooding

Western Washington			*Eastern Washington*		
Species	Role	Soil conditions	Species	Role	Soil conditions
Red alder	P,N	D,M,W	Russian olive	P,N	D
Shore pine	P,Cl	D,Fl	Black Locust	P,N	D,M
Ponderosa pine	P,Cl	D	Poplar	P	W,Fl
Douglas fir	P,Cl	D,M	Lodgepole pine	P,Cl	D,Fl
Poplar	P	W,Fl	Ponderosa pine	P,Cl	D
Big leaf Maple	P,C	M	Juniper	P,Cl	D
Willow (shrub)	P	M,W,Fl	Serviceberry (shrub)	P	W,M
Tree lupine (shrub)	P,N	M,W	Sagebrush	P	D
			Bitter brush	P,	D
			Willow (shrub)	P	M,W,Fl
			Tree lupine (shrub)	P,N	M,W

Western Washington

Fertilizer is usually necessary to re-establish vegetation for parts or all of some mined sites and can be tailored to each site's characteristics and soil. Amounts and composition can be determined through a soil analysis, which can be done by the County Extension or local soil testing labs. Fertilizer should be worked into the top 4 inches of soil. Time-release fertilizer is best; otherwise, re-fertilization may be necessary. Adding organic amendments (such as manure) may require permission from health authorities. Less nitrogen will be required if nitrogen-fixing species are planted. Normally, a balanced fertilizer (16-16-16 or 10-20-20) should be used, but fertilizers can be designed to more effectively correct specific soil deficiencies.

For upland sites in western Washington, good soils can be established with the following amendment application rates:

Nitrogen	50 lb per acre
Phosphoric acid	50 lb per acre
Potassium	50 lb per acre
Lime (for acid soils [pH<7])	~1,700 lb per acre

Grass and legume seeding requirements also vary from site to site, depending on slope orientation, soil type, and precipitation, among other factors. Planting should be done between April 1 and June 30 and from September 15 through October 31. If planting is done in July and August, irrigation will be required. Plantings between November 1 and March 31 need immediate mulching to provide a protective cover from the weather.

Table 2. General seed mixes and rates of application per acre for western Washington; these mixes should be adjusted to meet specific needs

For dry upland sites:		*For wetlands or wet sites:*	
Sicklekeeled lupine (N-fix)	30 lb	Red top	20 lb
Creeping red fescue	30 lb	Birdsfoot trefoil	20 lb
Perennial rye	15 lb	Creeping red fescue	20 lb
Orchard grass	25 lb	Total	60 lb
Colonial bent grass	5 lb		
White clover	5 lb		
Cereal rye	5 lb		
Total	115 lb		

Seed mixes offer better chances of successful revegetation because a variety of species is included. Some successful mixes and application rate per acre are given in Table 2.

It is not critical to have the exact seed mix listed in Table 2 as long as the components are present. Many seed stores have prepared mixes that approximate those in Table 2 and may be cheaper than custom mixes. Seed mixes and fertilizer cost about $100 to $125 per acre, but price will vary with quantity of seed and fertilizer. Using nitrogen-fixing species will assure that the site becomes self-sustaining sooner and will require fewer fertilizer treatments.

Seeds should be covered with topsoil or mulch no deeper than a half inch. Regardless of how burial is accomplished, seed should be covered to assure germination and survival.

Wetland Seed Mixtures and Plants

Establishing functional self-sustaining marshes, lakes, or bogs can take years, but they contribute significantly to an area's ecological health. Consulting a biologist with expertise in wetlands will aid significantly in creating successful new wetlands. As a general guide, apply the wetland seed mixture in Table 2 at a rate of 60 lb/acre and, in addition, plant tubers for cattail, bulrush, and slough sedge, and willow cuttings. Invasive plants such as reed canarygrass or purple loosestrife should not be used (Washington Department of Ecology, 1991). Water should be no deeper than 3 feet and in much of the site should be less than 18 inches deep. (See Wetlands and Lakes below). Nitrate fertilizers should not be used.

Eastern Washington

All the basic principles for planting and fertilization discussed above apply to eastern Washington. In this part of the state, planting so that vegetation covers every square foot of ground is impractical. The climate and, in some places, lack of topsoil mean that special care is needed to establish vegetation on mined sites. Segmental reclamation offers an opportunity to test various mixes and amendments.

Especially in this part of the state, topsoil from each mine segment should be carefully preserved for reclamation. Once topsoil has been distributed and the seedbed prepared, planting one of the mixes for eastern Washington listed in Table 3 will start the revegetation process. Lupine and clover are recommended because they fix nitrogen and are adapted to a wide range of conditions. However, the characteristics of each site should be evaluated to assure selection of an appropriate seed and plant mix. Generally, vegetation on areas adjacent to the mine indicates what will survive. Shrubs and trees should be selected to complete vegetation of the site (Table 1).

SUBSEQUENT LAND USES

Wetlands and Lakes

Sand and gravel pits in which the pit floor is seasonally or permanently below the water table provide excellent opportunities to create wetlands, lakes, and habitat for wildlife and fish. Productive lakes and wetlands have irregular shorelines and areas of shallow water (Fig. 4; Michalski and others,

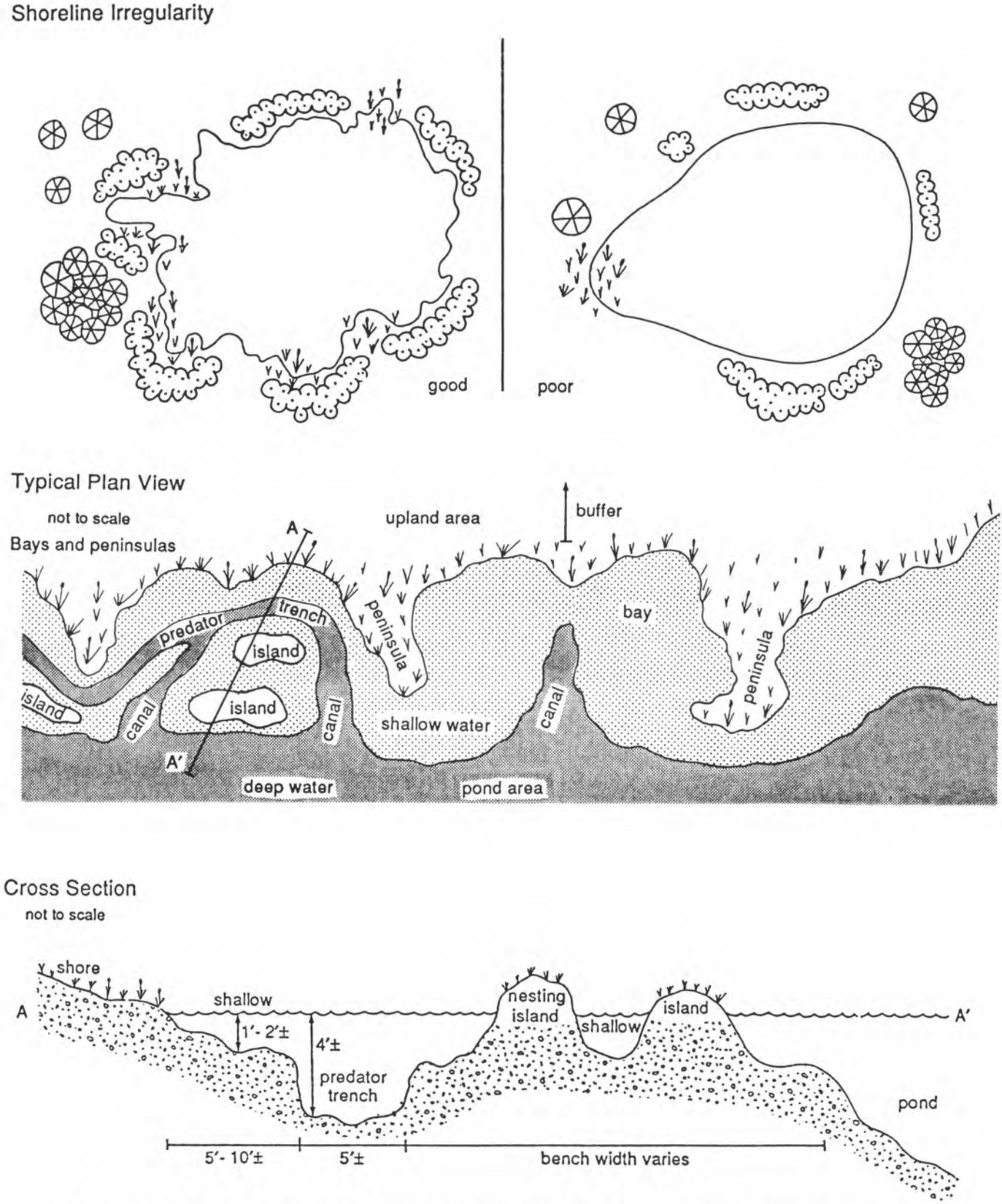


Figure 4. *Shoreline irregularity*—Shorelines of ponds in reclaimed mines that will be used as wildlife habitat should be irregular and planted for cover. The shape of the pond on the left is preferred to that of the pond on the right.

Plan view and cross section—Plan and cross section of a well-designed irregular wetland or pond shoreline. Note large areas of shallow water. Steep slopes along parts of the shore will discourage the growth of cattails and emergent plants and provide clear access to the pond. Nesting sites are provided. The trench discourages predators, but the shallow water offers sites for food and cover plantings. Islands can be constructed from fill, unmined material, or sediments saved from digging the trench.

1987; Herricks, 1982). In a typical sand and gravel mine, deep areas from which all the commercial material has been recovered will make up the majority of a lake, but shallow areas must be provided around the margins of the excavation to avoid creating a sterile wetland.

Some recommendations for creating lakes and wetlands that will provide desirable habitat for wildlife and fish are:

- Early use of the lake to dispose of sediment from retention ponds will provide a substrate for aquatic plants.
- Areas where the water is more than 10 feet deep, as well as benches and shoals rimmed by water less than 2 feet deep, should be provided. Ideally, 25 percent of the lake should be shallow and the nearshore lakebed nearly flat, 25 percent 2 to 6 feet deep, and the remainder more than 10 feet deep. Shallow areas may not be desirable or possible in all parts of a lake. However, from a wetland perspective, the more shallow areas, the better.
- Large, unusable material such as boulders can be placed in deep water as cover for fish and a hard substrate for insects, snails, and other invertebrates. Some tree and stump debris from clearing the site can also be placed in lakes. Submerged crowns of trees and brush piles anchored along steep banks provide excellent cover.
- At least half the lake shoreline should be constructed as shown in Figure 4. Shallow shorelines should slope not more than 5H:1V.
- Nesting islands should be more than 3 feet in diameter. Irregular shapes are preferable. More small islands are better than a few large ones. Mine waste or material from canals and predator trenches can be used to construct islands.
- Wherever possible 8 inches of topsoil should be placed on banks, islands, and shallow areas, especially where vegetation is desired.
- Areas of undisturbed, native vegetation along the shoreline (riparian zones) are important to wildlife and fish. Buffers should be at least 100 feet wide along creeks. Buffers need not surround a lake, but the more extensive and continuous the buffer, the better.
- Planting areas along the wetland with native riparian trees and shrubs (poplar, red alder, willow, shore pine, big-leaf maple, western red cedar, western hemlock, Oregon ash) and grasses that provide nesting cover can accelerate restoration of habitat (Washington Department of Ecology, 1990).
- If access for boating, swimming, or fishing is planned, some segments of the shore should slope steeply to limit growth of emergent plants and to facilitate access to the water. Recreational access should be as far from waterfowl nesting habitat as possible.

Table 3. Seed mixes and application rates per acre for eastern Washington

Mix 1:		*Mix 2:*	
Lupine	5 lb	Pubescent wheatgrass (sod-former)	12 lb
Indian ricegrass	5 lb	Sheep Fescue (bunchgrass)	6 lb
Desert wheatgrass	5 lb	Alfalfa (ladak) or yellow sweetclover	4 lb
Thickspike wheatgrass	5 lb	Total	22 lb
Sand dropseed	2 lb		
Big bluegrass	1 lb		
Sheep fescue	1 lb		
Total	24 lb		
Mix 3:		*Mix 4:*	
Sherman big bluegrass (bunchgrass)	8 lb	Crested wheatgrass (bunchgrass)	8 lb
Sheep fescue (bunchgrass)	6 lb	Canby bluegrass (bunchgrass)	6 lb
Alfalfa (ladak) or yellow sweetclover	4 lb	Alfalfa (ladak) or yellow sweetclover	4 lb
Total	18 lb	Total	18 lb
Mix 5 (south and west slopes):		*Mix 6 (north and east slopes):*	
Crested wheatgrass (bunchgrass)	15 lb	Beardless wheatgrass	12 lb
Smooth brome	10 lb	Orchard grass	8 lb
Cereal rye	15 lb	Total	20 lb
Total	40 lb		

Mines that are located along rivers and in flood plains must be reclaimed as lakes and wetlands. Erosion and attempts to control the river with dikes or revetments are the main problems associated with these mining operations. When a river changes its course catastrophically, whether as a natural or induced process, the alteration is known as avulsion. If a mine is located on the inside of a meander, the river is likely to avulse when it enters the mine during a flood. The Yakima River moved 1,800 feet laterally during one night when it entered a mine. (See Dunne and Leopold, 1978.) Avulsion can cause severe erosion and property loss. On the other hand, building dikes to prevent avulsion can deflect the river's erosive force to a new location, and dikes can diminish the quality of the subaqueous habitat.

Successful reclamation of mines in these settings depends on site selection and understanding river dynamics, considering both rates of course alteration and erosion as well as the capacity to transport sand and gravel (Collins and Dunne, 1990). Floodplains where rivers have wide meander paths need buffer zones designed to protect against river avulsion and to provide long-term stability for the reclaimed mine.

Upland Wildlife Habitat

If an upland site is to be reclaimed as wildlife habitat, biological diversity is the goal. Appropriate plants should be provided for food and cover for all seasons. Basic vegetative components are:

- Conifers, hardwoods, grasses, and legumes that provide protective seasonal shelter, summer nesting cover, and some food (leaves, seeds, or nuts), and
- Plants that provide nectar or other food for insects.

Structural components listed in Michalski and others (1987) are:

- Nest boxes and nest platforms, dead trees, fallen trees, and other perches or roosts for birds,
- Brush and rock piles for cover and denning for mammals and reptiles,
- Cut banks and irregular pit-floor topography,
- Water, and
- Some open space with only grasses and legumes.

Wildlife management strategies and restricting access to the area will also contribute to successful habitat restoration.

Segmental reclamation facilitates plant communities developing in a range of ecological succession stages. A combination of natural reseeding and intentional planting is the most effective means of establishing diverse and prosperous vegetation for wildlife.

Figure 5. This reclaimed segment of a sand and gravel pit has been replanted for forestry. Mine operator Milt Emerick stands next to a 4-year-old Douglas fir. Before the trees were planted, the pit floor was ripped, and wood chips and bark waste were tilled in to build soil. A grass/legume mix was planted the first year, and in the second, 2-year-old Douglas fir nursery stock was planted.

Trees are the key to useful wildlife habitat. Upland trees most valuable for wildlife are those that bear nuts or berries. However, most reclaimed sites cannot support these types of trees immediately. Conifer plantings should be restricted to small patches because these function principally as windbreaks and shelter but have little food value. Red alders improve the soil by fixing nitrogen and are good for reclamation west of the Cascades. East of the Cascades, Russian olive and black locust are generally good choices; they also fix nitrogen, but will not survive in dry sites.

Forest Production

Reclamation as forest land can result in revenue and lower taxes for the private landowner. Assistance for reclamation for forestry is available from the DNR regional offices. (See Norman, 1992.) For example, the forestry incentives program allows for a federal cost-sharing of up to $10,000. Eligible reclamation includes the normal forest practices necessary to establish seedlings, site preparation for natural regeneration, and control of competing vegetation. Most mined properties have the potential for forest production (Fig. 5). However, sites that should not be considered for forestry have some or all of the following characteristics: area less than 10 acres, slopes steeper than 3H:1V, soil depths less than 20 inches over bedrock, or a high permanent water table (unless poplar trees are to be planted in a wet site).

Residential, Industrial or Commercial Uses

Minimum reclamation is required for these uses. Slopes should be stabilized, shaped, drained, and revegetated with a grass/legume mixture (Figs. 6 and 7). Some topsoil replacement may be necessary. The pit floor must be graded for proper drainage.

Agricultural Uses

Full recovery of mined land to be used for crops takes many years. Reclamation for agriculture requires thorough planning and preparation; essential tasks are initial separation of the A, B, and C soil horizons and restoring topsoil or subsoil that has had minimum degradation. Restored topsoil should be at least 8 inches thick and the subsoil at least 3 feet thick. Loss and damage of topsoil through burial, stockpiling, or moving can be minimized by segmental reclamation. Topsoil should not be stored for prolonged periods.

Proper drainage can be achieved by shaping slopes to eliminate sheet wash. Poor drainage is likely to cause excessively wet soil, which is not desirable for most crops.

Ripping and tilling a pit floor will loosen the surface for planting and is essential for restoring soil porosity and structure. Removing cobbles and large gravel may be necessary before planting some sites.

The first 5 years of reclamation should be dedicated to growing grass/legume mixes in which legumes are the main constituent. During this time, no grazing or harvesting should occur; instead, crops should be tilled into the soil (Mackintosh and Mozuraitis, 1982). Legumes, preferably alfalfa, which is deep rooting, reduce compaction, fix nitrogen, and return organic matter to the soil. (Lupine should not be planted because some species are poisonous to livestock.)

Crops on slopes that range from 6H:1V to 10H:1V are easy to harvest. However, gentle final slopes usually mean that wider setbacks or shallower pits will be required during mining. It

Figure 6. Reclamation of sand and gravel pits for industrial or commercial uses such as shopping centers generally requires less effort than for other subsequent uses because the pit floor is flat and paved. The mined slope at this site has been revegetated with both trees and grasses, and the toe of the slope is held by large rocks. Stormwater drainage is directed to deeper parts of the former pit.

may be preferable to reclaim the north- and east-facing pit margins at the steepest reasonable slope, thus maximizing the area of flat pit floor (Fig. 8). Increased production on flat floors may offset lost production on northern and eastern exposures.

Landfills and Garbage Dumps

Backfilling a sand and gravel mine with household garbage, construction debris, or wood debris is allowed only with written approval of the local health agency. Because sand and gravel deposits are porous and permeable, contaminants travel quickly to ground water, streams, and lakes. Rain supplies oxygen that promotes the growth of methanogenic bacteria. The Department of Natural Resources strongly discourages the use of sand and gravel mines as landfills.

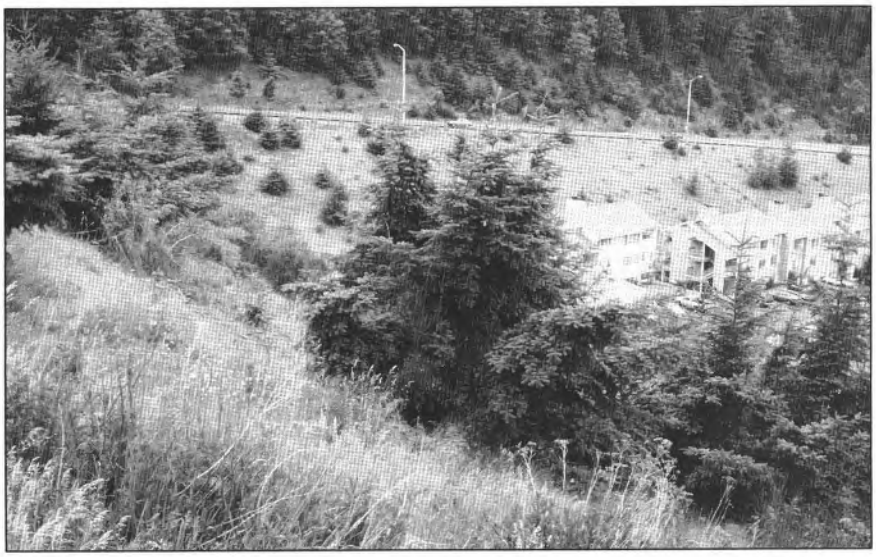


Figure 7. In urban areas, reclaimed sand and gravel pits can accommodate apartment complexes. Slopes at this location have been revegetated with grasses, legumes, and Douglas fir. (Photo by Dave Pierce, Department of Natural Resources, South Puget Sound Region).

REFERENCES CITED

Collins, B. D.; Dunne, Thomas, 1990, Fluvial geomorphology and river-gravel mining—A guide for planners, case studies included: California Division of Mines and Geology Special Publication 98, 29 p. [Includes some Washington case studies; methods of measuring transport and the effects of gravel extraction are discussed.]

Coppin, N. J.; Bradshaw, A. D., 1982, Quarry reclamation—The establishment of vegetation in quarries and open pit non-metal mines: Mining Journal Books [London, England], 112 p.

Dunne, Thomas; Leopold, L. B., 1978, Water in environmental planning: W. H. Freeman and Company, 818 p.

Dunne, Thomas; Dietrich, W. E.; Humphrey, N. F.; Tubbs, D. W., 1981, Geologic and geomorphic implications for gravel supply. *In* Proceedings from the conference on salmon-spawning gravel—A renewable resource in the Pacific Northwest?: Washington Water Research Center Report, p. 75-100.

Herricks, E. E., 1982, Development of aquatic habitat potential of gravel pits. *In* Svedarsky, W. D.; Crawford, R. D., editors, Wildlife values of gravel pits—Symposium proceedings: University of Minnesota Agricultural Experiment Station Miscellaneous Publication 17-1982, p. 196-207.

Mackintosh, E. E.; Mozuraitis, E. J., 1982, Agriculture and the aggregate industry—Rehabilitation of extracted sand and gravel lands to an agricultural after-use: Ontario Ministry of Natural Resources Industrial Mineral Background Paper 3, 39 p.

Michalski, M. F. P.; Gregory, D. R.; Usher, A. J., 1987, Rehabilitation of pits and quarries for fish and wildlife: Ontario Ministry of Natural Resources, Land Management Branch, 59 p.

Miller, J. E.; Frederick, R. H.; Tracey, R. J., 1973, Precipitation-frequency atlas of the western United States—Vol. IX—Washington: U.S. Department of Commerce National Oceanic and Atmospheric Administration Atlas 2, 43 p.

Norman, D. K., 1992, Surface mining in Washington—Some regulatory responsibilities of various federal, state, and local government agencies, 1992: Washington Division of Geology and Earth Resources Open File Report 92-5, 22 p.

Shank, Dale, editor, 1990, Hortus Northwest—A Pacific Northwest native plant directory and journal: Hortus Northwest, no. 2, 50 p.

Washington Department of Ecology, 1991, Stormwater management manual for the Puget Sound Basin: Washington Department of Ecology Publication #90-73, 1 v.

Washington State University Cooperative Extension, 1983, Washington interagency guide for conservation and forage planting: Washington State University Cooperative Extension MISC.0058, 70 p.

Van Kekerix, Lorraine; Kay, B. L., 1986, Revegetation of disturbed land in California—An element of mined land reclamation: California Division of Mines and Geology Open-File Report 86-14, 105 p. ■

Figure 8. Segment of a mine reclaimed for agriculture is shown with a cut slope at the right edge. Active mining continues (top of photo). The productive agricultural area is the flat pit floor, which has been planted in raspberries. Sparse areas in the raspberries are caused by poor drainage. The steep (3H:1V) banks maximize productive agricultural land and are planted with a grass/legume mix. (Photo by Jeff Griffin, Whatcom County Planning Department.)

National Geologic Mapping Act of 1992

Public Law 102-285—May 18, 1992 [H.R. 2763]

An Act
To enhance geologic mapping of the United States,
and for other purposes.
Be it enacted by the Senate and House of Representatives
of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "National Geologic Mapping Act of 1992".

SECTION 2. FINDINGS AND PURPOSE.

(a) Findings.—The Congress finds and declares that—
- (1) during the past 2 decades, the production of geologic maps has been drastically curtailed;
- (2) geologic maps are the primary data base for virtually all applied and basic earth-science investigations, including—
  - (A) exploration for and development of mineral, energy, and water resources;
  - (B) screening and characterizing sites for toxic and nuclear waste disposal;
  - (C) land use evaluation and planning for environmental protection;
  - (D) earthquake hazards reduction;
  - (E) predicting volcanic hazards;
  - (F) design and construction of infrastructure requirements such as utility lifelines, transportation corridors, and surface-water impoundments;
  - (G) reducing losses from landslides and other ground failures;
  - (H) mitigating effects of coastal and stream erosion;
  - (I) siting of critical facilities; and
  - (J) basic earth-science research;
- (3) Federal agencies, State and local governments, private industry, and the general public depend on the information provided by geologic maps to determine the extent of potential environmental damage before embarking on projects that could lead to preventable, costly environmental problems or litigation;
- (4) the combined capabilities of State, Federal, and academic groups to provide geologic mapping are not sufficient to meet the present and future needs of the United States for national security, environmental protection, and energy self-sufficiency of the Nation;
- (5) States are willing to contribute 50 percent of the funding necessary to complete the mapping of the geology within the State;
- (6) the lack of proper geologic maps has led to the poor design of such structures as dams and waste-disposal facilities;
- (7) geologic maps have proven indispensable in the search for needed fossil-fuel and mineral resources; and
- (8) a comprehensive nationwide program of geologic mapping is required in order to systematically build the Nation's geologic-map data base at a pace that responds to increasing demand.

(b) Purpose.—The purpose of this Act is to expedite the production of a geologic-map data base for the Nation, to be located within the United States Geological Survey, which can be applied to land-use management, assessment, and utilization, conservation of natural resources, groundwater management, and environmental protection.

SECTION 3. DEFINITIONS.

As used in this Act:
- (1) The term "advisory committee" means the advisory committee established under section 5.
- (2) The term "Director" means the Director of the United States Geological Survey.
- (3) The term "geologic mapping program" means the National Cooperative Geologic Mapping Program established by section 4(a).
- (4) The term "Secretary" means the Secretary of the Interior.
- (5) The term "Survey" means the United States Geological Survey.

SECTION 4. GEOLOGIC MAPPING PROGRAM.

(a) Establishment.—There is established in the United States Geological Survey [USGS] a National Cooperative Geologic Mapping Program. The geologic mapping program shall be developed in consultation with the advisory committee and shall be designed and administered to achieve the objectives set forth in subsection (c).

(b) Responsibilities of USGS.—
- (1) The Survey shall be the lead Federal agency responsible for planning, developing priorities, coordinating, and managing the geologic mapping program. In carrying out this paragraph, the Secretary, acting through the Director, shall—
  - (A) develop a geologic mapping program implementation plan in accordance with section 6, which plan shall be submitted to the Committee on Interior and Insular Affairs of the House of Representatives and the Committee on Energy and Natural Resources of the Senate within 300 days after the date of enactment of this Act;
  - (B) appoint, with the advice and consultation of the State geological surveys, the advisory committee within 90 days after the date of enactment of this Act in accordance with section 5; and
  - (C) within 210 days after the date of enactment of this Act, submit a report to the Committee on Energy and Natural Resources of the United States Senate and to the Committee on Interior and Insular Affairs of the House of Representatives identifying—
    - (i) how the Survey will coordinate the development and implementation of the geologic mapping program;
    - (ii) how the Survey will establish goals, mapping priorities, and target dates for implementation of the geologic mapping program;
    - (iii) how long-term staffing plans for the various components of the geologic mapping program will lead to successful implementation of the geologic mapping program; and
    - (iv) the degree to which geologic mapping activities traditionally funded by the Survey, including the use of commercially available aerial photography, geodesy, professional land surveying, photogrammetric mapping, cartography, photographic processing, and related services, can be contracted to professional private mapping firms.
- (2) In addition to paragraph (1), the Secretary, acting through the Director, shall be responsible for developing, as soon as practicable—
  - (A) in cooperation with the State geological surveys, other Federal and State agencies, public and private sector organizations and academia, the geologic-map data base; and
  - (B) maps and mapping techniques which achieve the objectives specified in subsection (c).

(c) Program Objectives.—The objectives of the geologic mapping program shall include—
- (1) determining the Nation's geologic framework through systematic development of geologic maps at scales appropriate to the geologic setting and the perceived applications, such maps to be contributed to the national geologic map data base;
- (2) development of a complementary national geophysical-map data base, geochemical-map data base, and a geochronologic and paleontologic data base that provide value-added descriptive and interpretive information to the geologic-map data base;
- (3) application of cost-effective mapping techniques that assemble, produce, translate and disseminate geologic-map information and that render such information of greater application and benefit to the public; and
- (4) development of public awareness for the role and application of geologic-map information to the resolution of national issues of land use management.

(d) Program Components.—The geologic mapping program shall include the following components:

(1) A Federal geologic mapping component, whose objective shall be determining the geologic framework of areas determined to be vital to the economic, social, or scientific welfare of the Nation. Mapping priorities shall be based on—
   (A) national requirements for geologic-map information in areas of multiple-issue need or areas of compelling single-issue need; and
   (B) national requirements for geologic-map information in areas where mapping is required to solve critical earth-science problems.

(2) A geologic mapping support component, whose objective shall be providing interdisciplinary support for the Federal Geologic Mapping Component. Representative categories of interdisciplinary support shall include—
   (A) establishment of a national geologic-map data base, established pursuant to section 7;
   (B) studies that lead to the implementation of cost-effective digital methods for the acquisition, compilation, analysis, cartographic production, and dissemination of geologic-map information;
   (C) paleontologic investigations that provide information critical to understanding the age and depositional environment of fossil-bearing geologic-map units, which investigations shall be contributed to a national paleontologic data base;
   (D) geochronologic and isotopic investigations that (i) provide radiometric age dates for geologic-map units and (ii) fingerprint the geothermometry, geobarometry, and alteration history of geologic-map units, which investigations shall be contributed to a national geochronologic data base;
   (E) geophysical investigations that assist in delineating and mapping the physical characteristics and three-dimensional distribution of geologic materials and geologic structures, which investigations shall be contributed to a national geophysical-map data base; and
   (F) geochemical investigations and analytical operations that characterize the major- and minor-element composition of geologic-map units, and that lead to the recognition of stable and anomalous geochemical signatures for geologic terrains, which investigations shall be contributed to a national geochemical-map data base.

(3) A State geologic mapping component, whose objective shall be determining the geologic framework of areas that the State geological surveys determine to be vital to the economic, social, or scientific welfare of individual States. Mapping priorities shall be determined by multirepresentational State panels and shall be integrated with national priorities. Federal funding for the State component shall be matched on a one-to-one basis with non-Federal funds.

(4) A geologic mapping education component, whose objectives shall be—
   (A) to develop the academic programs that teach earth-science students the fundamental principles of geologic mapping and field analysis; and
   (B) to provide for broad education in geologic mapping and field analysis through support of field teaching institutes.

   Investigations conducted under the geologic mapping education component shall be integrated with the other mapping components of the geologic mapping program, and shall respond to priorities identified for those components.

SECTION 5. ADVISORY COMMITTEE.

(a) Establishment.—There shall be established a sixteen member geologic mapping advisory committee to advise the Director on planning and implementation of the geologic mapping program. The President shall appoint one representative each from the Environmental Protection Agency, the Department of Energy, the Department of Agriculture, and the Office of Science and Technology Policy. Within 90 days and with the advice and consultation of the State Geological Surveys, the Secretary shall appoint to the advisory committee 2 representatives from the Survey (including the Chief Geologist, as Chairman), 4 representatives from the State geological surveys, 3 representatives from academia, and 3 representatives from the private sector.

(b) Duties.—The advisory committee shall—
   (1) review and critique the draft implementation plan prepared by the Director pursuant to section 6;
   (2) review the scientific progress of the geologic mapping program; and
   (3) submit an annual report to the Secretary that evaluates the progress of the Federal and State mapping activities and evaluates the progress made toward fulfilling the purposes of this Act.

SECTION 6. GEOLOGIC MAPPING PROGRAM IMPLEMENTATION PLAN.

The Secretary, acting through the Director, shall, with the advice and review of the advisory committee, prepare an implementation plan for the geologic mapping program. The plan shall identify the overall management structure and operation of the geologic mapping program and shall provide for—

(1) the role of the Survey in its capacity as overall management lead, including the responsibility for developing the national geologic mapping program that meets Federal needs while simultaneously fostering State needs;

(2) the responsibilities accruing to the State geological surveys, with particular emphasis on mechanisms that incorporate their needs, missions, capabilities, and requirements into the nationwide geologic mapping program;

(3) mechanisms for identifying short- and long-term priorities for each component of the geologic mapping program, including—
   (A) for the Federal geologic mapping component, a priority-setting mechanism that responds both to (i) Federal mission requirements for geologic-map information, and (ii) critical scientific problems that require geologic-map control for their resolution;
   (B) for the geologic mapping support component, a strong interdisciplinary research program plan in isotopic and paleontologic geochronology, geophysical mapping, and process studies to provide data to and interpret results from geologic mapping;
   (C) for the State geologic mapping component, a priority-setting mechanism that responds to (i) specific intrastate needs for geologic-map information, and (ii) interstate needs shared by adjacent entities that have common requirements; and
   (D) for the geologic mapping education component, a priority-setting mechanism that responds to requirements for geologic-map information that are driven by Federal and State mission requirements;

(4) a description of the degree to which the Survey can acquire, archive, and use Side-Looking Airborne Radar (SLAR) or Interferometric Synthetic Aperture Radar (IFSAR) data in a manner that is technically appropriate for geologic or related mapping studies;

(5) a mechanism for adopting scientific and technical map standards for preparing and publishing general-purpose and special-purpose geologic maps to:
   (A) assure uniformity of cartographic and scientific conventions, and
   (B) provide a basis for judgment as to the comparability and quality of map products; and

(6) a mechanism for monitoring the inventory of published and current mapping investigations nationwide in order to facilitate planning and information exchange and to avoid redundancy.

SECTION 7. NATIONAL GEOLOGIC-MAP DATA BASE.

(a) Establishment.—The Survey shall establish a national geologic-map data base. Such data base shall be a national archive that includes all maps developed pursuant to this Act, the data bases developed pursuant to the investigations under sections (4)(d)(2)(C), (D), (E), and (F), and other maps and data as the Survey deems appropriate.

(b) Standardization.—Geologic maps contributed to the national archives should have standardized format, symbols, and technical attributes so that archival information can be assimilated, manipu-

lated, accessed, exchanged, and compared efficiently and accurately.

SECTION 8. ANNUAL REPORT.

The Secretary shall, within 90 days after the end of each fiscal year, submit an annual report to the Committee on Interior and Insular Affairs of the House of Representatives and the Committee on Energy and Natural Resources of the Senate describing the status of the nationwide geologic mapping program, and describing and evaluating progress achieved during the preceding fiscal year in developing the national geologic-map data base. Each report shall include any recommendations for legislative or other action as the Secretary deems necessary and appropriate to fulfill the purposes of this Act.

SECTION 9. AUTHORIZATION OF APPROPRIATIONS.

There is authorized to be appropriated to carry out this Act the following:

(1) For Federal mapping activities under this Act, $12,500,000 for fiscal year 1993, $14,000,000 for fiscal year 1994, $16,000,000 for fiscal year 1995, and $18,000,000 for fiscal year 1996.
(2) For Federal support activities under this Act, $9,500,000 for fiscal year 1993, $10,000,000 for fiscal year 1994, $10,500,000 for fiscal year 1995, and $11,000,000 for fiscal year 1996.
(3) For State mapping activities under this Act, $15,000,000 for fiscal year 1993, $18,000,000 for fiscal year 1994, $21,000,000 for fiscal year 1995, and $25,000,000 for fiscal year 1996.
(4) For educational support activities under this Act, $500,000 for fiscal year 1993, $750,000 for fiscal year 1994, $1,000,000 for fiscal year 1995, and $1,500,000 for fiscal year 1996.

SECTION 10. UNITED STATES GEOLOGICAL SURVEY AND UNITED STATES BUREAU OF MINES.

(a) United States Geological Survey.—The Geological Survey established by the Act of March 3, 1879 (43 U.S.C. 31(a)), is designated as and shall hereafter be known as the United States Geological Survey.
(b) United States Bureau of Mines.—The Bureau of Mines established by the Act of May 16, 1910 (30 U.S.C. 1), is designated as and shall hereafter be known as the United States Bureau of Mines.

Approved May 18, 1992.

Selected Additions to the Library of the Division of Geology and Earth Resources

May 1992 through July 1992

THESES

Andrews, Robert Sanborn, 1965, Modern sediments of Willapa Bay, Washington—A coastal plain estuary: University of Washington Master of Science thesis, 60 p.

Butterfield, David Allen, 1990, Phase separation in submarine hydrothermal systems—Evidence from the Juan de Fuca Ridge: University of Washington Doctor of Philosophy thesis, 185 p.

Chiao, Ling-Yun, 1991, Membrane deformation rate and geometry of subducting slabs: University of Washington Doctor of Philosophy thesis, 144 p.

Dailey, Anne Drinkhouse, 1985, Chemical and physical fluid characterization during low grade metamorphism: University of Washington Master of Science thesis, 80 p.

Johnson, George Edward, 1991, Estimating groundwater recharge beneath different slope positions in the Palouse Formation using a numerical unsaturated flow model: Washington State University Master of Science thesis, 111 p.

Jones, Carolyn Jessica, 1981, The marine geochemistry of nutrients and trace metals in the Cascadia Basin: University of Washington Master of Science thesis, 166 p.

Karsten, Jill Leslie, 1988, Spatial and temporal variations in the petrology, morphology and tectonics of a migrating spreading center—The Endeavour segment, Juan de Fuca Ridge: University of Washington Doctor of Philosophy thesis, 329 p.

Kuhlman, John G., 1986, Three-dimensional and quasi three-dimensional groundwater modeling at a hazardous waste site: Washington State University Master of Science thesis, 149 p.

Major, Jon J., 1984, Geologic and rheologic characteristics of the May 18, 1980 southwest flank lahars at Mount St. Helens, Washington: Pennsylvania State University Master of Science thesis, 225 p., 12 plates.

Malin, Richard Stephen, 1991, Interpretation of the thermal behavior of groundwater in an alluvial terrace—Bonneville Dam, Columbia Gorge, Oregon: Portland State University Master of Science thesis, 139 p.

Michaels, Sarah, 1990, The processes and structures of earthquake information exchange in the Province of British Columbia and the State of Washington—A comparative study of policy communities: University of Colorado Doctor of Philosophy thesis, 367 p.

Shevenell, Lisa, 1990, Chemical and isotopic investigation of the new hydrothermal system at Mount St. Helens, Washington: University of Nevada, Reno Doctor of Philosophy thesis, 282 p.

Warnock, Andrew C., 1992, Paleomagnetism and tectonics of the Crescent Formation, northern Olympic Mountains, Washington: Western Washington University Master of Science thesis, 59 p.

White, Daniel J., 1988, Three-dimensional modeling of seismic structure in the Puget Sound region: Pennsylvania State University Master of Science thesis, 64 p.

U.S. GEOLOGICAL SURVEY REPORTS

Published Reports

Dickinson, K. A., editor, 1992, Short papers of the U.S. Geological Survey uranium workshop, 1990: U.S. Geological Survey Circular 1069, 56 p.

Lockwood, Millington; Elms, J. D.; Lockridge, P. A.; Moore, G. W.; Nishenko, S. P.; Simkin, Tom; Newhall, Chris, 1990, Natural hazards map of the Circum-Pacific region—Pacific Basin sheet: U.S. Geological Survey Circum-Pacific Map Series CP-35, 1 sheet, scale 1:17,000,000, with 31 p. text.

Rubin, Penni; Robbins, E. I., 1992, What's under your feet?: U.S. Geological Survey, 42 p.

U.S. Geological Survey, 1992, U.S. Geological Survey report to the Association of American State Geologists for fiscal years 1991–1993: U.S. Geological Survey, 38 p.

Walker, G. W.; MacLeod, N. S., 1991, Geologic map of Oregon: U.S. Geological Survey, 2 sheets, scale 1:500,000.

Contract Reports

Crosson, R. S., 1988, Earthquake hazards research in the Pacific Northwest; Final technical report—1987: U.S. Geological Survey contract report, 1 v.

Somerville, P. G., 1989, Simulation and empirical studies of strong ground motion attenuation in the Seattle–Portland region; Final report: U.S. Geological Survey [contract report], 1 v.

Open-File Reports

Driedger, C. L.; Walder, J. S., 1991, Recent debris flows at Mount Rainier: U.S. Geological Survey Open-File Report 91-242, 2 p.

Goldfinger, Chris; Kulm, L. D.; Yeats, R. S.; Appelgate, Bruce; MacKay, M. E.; Cochrane, G. R., 1991, Active strike-slip faulting and folding of the Cascadia plate boundary and forearc in central and northern Oregon: U.S. Geological Survey Open-File Report 91-441-S, 42 p.

Jacobson, M. L., compiler, 1992, National Earthquake Hazards Reduction Program, summaries of technical reports Volume XXXIII: U.S. Geological Survey Open-File Report 92-258, 2 v. (1019 p.)

McGee, K. A., 1992, Volcanic-plume data from Mount St. Helens during 1980–88: U.S. Geological Survey Open-File Report 92-361, 24 p.

Niem, W. A.; Niem, A. R., 1992, Ages of rocks in southwestern Washington and northwestern Oregon as indicated by paleontological and isotopic dates: U.S. Geological Survey Open-File Report 92-344, 115 p., 2 plates.

Peterson, C. D.; Darienzo, M. E., 1991, Discrimination of climatic, oceanic and tectonic mechanisms of cyclic marsh burial from Alsea Bay, Oregon, U.S.A.: U.S. Geological Survey Open-File Report 91-441-C, 53 p.

Rogers, A. M.; Walsh, T. J.; Kockelman, W. J.; Priest, G. R., 1991, Earthquake hazards in the Pacific Northwest—An overview: U.S. Geological Survey Open-File Report 91-441-O, 74 p., 1 plate.

Swanson, D. A., 1992, Geologic map of the McCoy Peak quadrangle, southern Cascade Range, Washington: U.S. Geological Survey Open-File Report 92-336, 36 p., 2 plates.

Yeats, R. S.; Graven, E. P.; Werner, K. S.; Goldfinger, Chris; Popowski, Thomas, 1991, Tectonics of the Willamette Valley, Oregon: U.S. Geological Survey Open-File Report 91-441-P, 47 p., 11 plates.

GEOLOGY AND MINERAL RESOURCES OF WASHINGTON

(and related topics)

Beak Consultants, Inc., 1992, Draft environmental impact statement, expansion of the Cannon mine industrial planned development zone: Chelan County Planning Department, 1 v.

Bela, James, 1992, Selected bibliography of the Cascadia subduction zone: Oregon Earthquake Awareness [Portland, Ore.], 15 p.

Bloomquist, R. G., 1991, Geothermal—A regulatory guide to leasing, permitting, and licensing in Idaho, Montana, Oregon, and Washington: U.S. Bonneville Power Administration, 275 p.

Gabrielse, H.; Yorath, C. J., editors, 1991, Geology of the Cordilleran orogen in Canada: Geological Survey of Canada Geology of Canada 4; Geological Society of America DNAG Geology of North America, Vol. G-2, 844 p., 12 plates in accompanying slipcase.

Johannessen, Jim, 1992, Net shore-drift of San Juan, and parts of Jefferson, Island and Snohomish Counties, Washington: Washington Department of Ecology, 1 v.

LaVassar, J. M.; Ordonez, G. A., 1991, Leader Lake seismic risk assessment: Washington Department of Ecology Open-File Technical Report 91-6, 1 v.

Manydeeds, S. A.; Smith, B. D., editors, 1991, Mineral frontiers on Indian lands: U.S. Bureau of Indian Affairs, 147 p.

Pelto, M. S., 1992, North Cascade glaciers—Their recent behavior; 1991 North Cascade Glacier Climate Project report: [Privately published by the author, Dudley, Mass.], 15 p.

Stevens, M. L.; Bursick, Robert, 1990, Washington State hydric soils guidebook: Washington Department of Ecology Publication 90-20, 33 p.

Thurston County Ground Water Advisory Committee, 1992, Summary—Northern Thurston County ground water management plan: Thurston County Ground Water Management Program, 38 p.

University of Washington Geophysics Program, 1992, Quarterly network report 92-A on seismicity of Washington and northern Oregon, January 1 through March 31, 1992: University of Washington Geophysics Program, 26 p.

Washington Department of Ecology, 1992, The Growth Management Act and the State Environmental Policy Act—A guide to interrelationships: Washington Department of Ecology Publication 92-7, 14 p.

Washington Department of Ecology, 1992, Puget Sound dredged disposal analysis—Management plan assessment report; Dredged material management year 1991 (June 16, 1990–June 15, 1991): Washington Department of Ecology Publication 92-36, 1 v.

Washington Department of Natural Resources, 1992, Draft E.I.S. environmental impact statement for the proposed forest practices rules and regulations and appendixes, proposed by Washington State Forest Practices Board: Washington Department of Natural Resources, 171 p.

White, W. W., III; Stebbins, Scott; Hillman, Thomas, 1990, Puget Sound region sand and gravel market study: U.S. Bureau of Mines Report BIA 64-III, 149 p.

Wolfe, J. A.; Wehr, W. C., 1992, Significance of the Republic Eocene fossil plants: Stonerose Interpretive Center [Republic, Wash.], 16 p. [reprinted from Washington Geology]

TIMBER, FISH AND WILDLIFE PROGRAM REPORTS

Benda, Lee; Miller, L. R., 1991, Geomorphological watershed analysis—A conceptual framework and review of techniques: Timber, Fish and Wildlife Program TFW-SH10-91-001, 54 p.

Bradley, J. B.; Whiting, P. J., 1992, A process-based stream classification system for small streams in Washington: Washington Department of Natural Resources; Timber, Fish and Wildlife Program TFW-SH11-91-001, 70 p.

Coho, Carol; Burges, S. J., 1991, Analysis of initiation mechanisms of dam-break floods in managed forests: University of Washington Department of Civil Engineering Water Resources Series Technical Report, 23 p. [Timber, Fish and Wildlife Program report]

Cupp, C. E., 1989, Valley segment type classification for forested lands of Washington: Timber, Fish and Wildlife Program TFW-AM-89-001, 1 v.

Dunne, Thomas; Montgomery, David; Dietrich, W. E., 1991, Proposal for research in geomorphological watershed analysis: Timber, Fish and Wildlife Program TFW-SH10-91-002, 1 v.

Golder Associates, 1991, Draft report on Phase I design of a slope hazard assessment system for Washington's forested land: Washington Department of Natural Resources; Timber, Fish and Wildlife Program TFW-SH13-91-001, 1 v.

Koler, T. E., 1992, Literature search of effects of timber harvest to deep-seated landslides: Timber, Fish and Wildlife Program TFW-SH5-91-001, 52 p.

Orsborn, J. F., 1990, Quantitative modeling of the relationships among basin, channel and habitat characteristics for classification and impact assessment: Timber, Fish and Wildlife Program TFW-AM3-90-010, 45 p.

Toth, Steven, 1991, A road damage inventory for the upper Deschutes River basin: Timber, Fish and Wildlife Program TFW-SH14-91-007, 1 v.

Wu, T. H.; Merry, C. J., 1990, Slope stability in the transient snow zone; I—Mapping the transient snow zone: Ohio State University Department of Civil Engineering [under contract to] Timber, Fish and Wildlife Program, 44 p.

MISCELLANEOUS TOPICS

Bobrowsky, Peter, compiler, 1992, Geologic hazards in British Columbia—Proceedings of the Geologic Hazards '92 Workshop: British Columbia Geological Survey Branch Open File 1992-15, 141 p.

Center for Strategic and International Studies Science and Technology Program, 1991, Managing the economic consequences of catastrophic earthquakes: Center for Strategic and International Studies [Washington, D.C.], 27 p.

Halvorson, G. A., 1991, Surface reclamation of sodic soil: U.S. Bureau of Mines research contract report, 55 p.

Love, C. B., 1991, Biomedical effects of volcanoes, January 1980 through September 1991: U.S. National Library of Medicine Current Bibliographies in Medicine 91-19, 28 p.

Niem, A. R.; MacLeod, N. S.; Snavely, P. D., Jr.; and others, 1992, Onshore-offshore geologic cross section, northern Oregon Coast Range to continental slope: Oregon Department of Geology and Mineral Industries Special Paper 26, 1 sheet, scale 1:100,000, with 10 p. text.

Sharma, Sunil, editor, 1992, Proceedings of the 28th symposium on engineering geology and geotechnical engineering: Idaho State University College of Engineering, 473 p.

Sunset Magazine, 1990, Sunset's guide to help you prepare for the next quake: Sunset Publishing Corporation [Menlo Park, Calif.], 16 p.

U.S. Bonneville Power Administration, 1987, Backgrounder—Understanding indoor radon: U.S. Bonneville Power Administration, 15 p.

U.S. Environmental Protection Agency, 1990, National mapping requirements program—Resources and guidance manual for identifying and reporting EPA's mapping requirements: U.S. Environmental Protection Agency Information Resources Management PM 218B, 1 v.

U.S. General Accounting Office, 1992, Transportation infrastructure—The nation's highway bridges remain at risk from earthquakes: U.S. General Accounting Office, 40 p.

U.S. Minerals Management Service; U.S. Bureau of Land Management; U.S. Forest Service, 1992, Mineral royalty transfer study: U.S. Minerals Management Service [Denver, Colo.?], 1 v.

VanCleave, J. P., 1991, Janice VanCleave's earth science for every kid—101 easy experiments that really work: John Wiley & Sons, Inc. [New York, N.Y.], 231 p. ■

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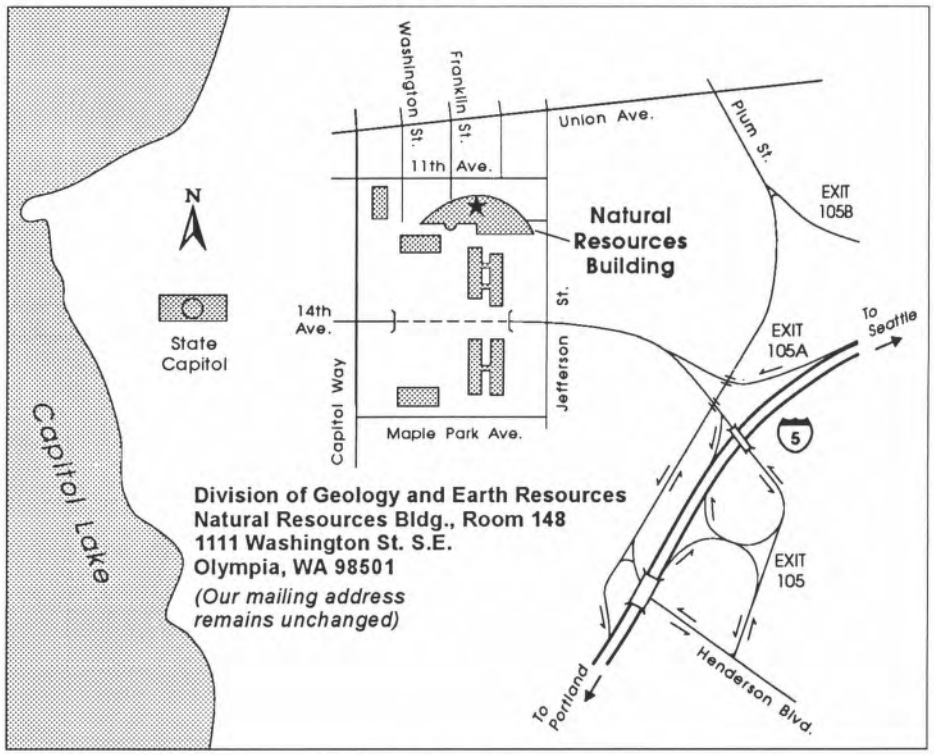

New Division Releases

Zircon fission-track ages for the Olympic subduction complex and adjacent Eocene basins, western Washington State, Open File Report 92-6, by Mark Brandon, Yale University, and Joseph Vance, University of Washington. This 71-page report contains the basic data to accompany a report by these authors now in press with the American Journal of Science. $2.31 + .19 (tax) = $2.50.

Preliminary maps of liquefaction susceptibility for the Renton and Auburn 7.5′ quadrangles, Washington, Open File Report 92-7, by Stephen P. Palmer. These maps are intended to provide land-use planners, developers, and other interested persons with a qualitative assessment of the potential for soil liquefaction during an earthquake. 24 pages, 2 plates, scale 1:24,000. Free.

Index to geologic and geophysical mapping of Washington, 1899–1983, Open File Report 92-8, compiled by Connie J. Manson. This report replaces Information Circular 77, which is out of print. This report also contains corrections to the previous version and notes the published version of superseded maps. 30 pages, 14 plates [color]. $22.10 + 1.90 (tax) = $24.00.

Publications of the Washington Division of Geology and Earth Resources, a list of Division publications and their prices current to August 1992. 32 pages. Free.

Survey Reminder

To date we have received only 30 responses to the reader survey included in the last issue. We need this information to serve you better. Please take the time to mail your survey response today!

New Address for Spokane USGS

U.S. Geological Survey
W. 904 Riverside Ave., Rm. 117
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Questions may be directed to the Earth Science Information Center (Room 135) at 509/353-2524, the Minerals Information Office (Room 133) at 509/353-2649, or the Branch of Western Mineral Resources (Room 117) at 509/353-2641.

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