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The Van Zandt Dike Landslide

and a Medley of Other Mass-Movement Features in the
Samish - South Nooksack Trough

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Introduction

The day's route goes north from Sedro-Woolley into Whatcom County. The main attraction is the large Van Zandt Dike landslide complex, a representative of a class of mega-landslides in this part of the North Cascades. We will spend most of the day walking and driving on this landslide, and talk about possible causes and mechanisms involved in such huge features, and the hazards and land-use ramifications associated with them.

But we will also see (some at 55 mph and from a distance) and discuss a sampling of other kinds of mass movement, including smaller landslides and debris flows, sackung, and volcanic debris flows (lahars). Many of the younger features were triggered by big winter storms of recent decades, especially 1979, 1983, 1990, and 1995. In 1983, after a week of heavy rain and snowmelt, an intense downpour on the night of January 10-11 turned many babbling brooks into raging torrents. Roughly two dozen debris flows were triggered in western Whatcom and Skagit Counties between 4:30 and 8:00 am on the 11th (Gerstel and Brunengo, 1994). November of 1990 brought two extraordinary rainstorms to northwest Washington, which together made it one of the wettest months on record; there were five major storms between November 1989 and April 1991. Debris torrents were triggered in many upland streams those winters, and flooding occurred several times in most of the rivers. Some of the effects are still apparent, including young floodplain erosion and deposition (now commonly occupied by young alder stands). The recent wet seasons since 1995 have also caused sliding and floods in some streams. You will see evidence of several of these processes through the day, and how they have been dealt with over the past years. In one stop, we will talk about the history of lahars flowing from Mount Baker down the forks of the Nooksack.

Bedrock Geology

In the North Cascades, uplift, structural deformation, and volcanism have created a complex mountain structure; hydroclimatic and geomorphic processes have carved it into an intricate landscape over a long history of erosion by mass wasting, water, and ice.

The bedrock geology of northwest Washington is complicated, and this guide contains only a brief survey of the topics most relevant to the trip. More detailed information can be found in the field-trip guides of Tabor and others (1989) and Haugerud and others (1994); in papers by Cowan (1994), and Tabor (1994); and in the text accompanying the 1:100,000 compilation maps for the region (Tabor and others, 1988, 1994; Whetten and others, 1988; Pessl and others, 1989). In particular, recent 7.5-minute quadrangle maps of the Deming—Kendall (Dragovich and others, 1997), and Sedro-Woolley North—Lyman (Dragovich and others, 1999, 2000) quads provides geologic maps at larger scales and more up-do-date bibliographies. This narrative is abstracted from these sources.

The geologic story of the North Cascades can be divided into several phases, each having, significant consequences for the current landscape. In the earlier stages, bedrock materials were generated and deformed, building the foundations of the current range; the rocks and structures partly control current processes and forms, but little vestige of the early landscape remains. The terrain features we see today are more the products of events during later periods, which most influenced the common forms of the mountains and the distribution of surficial materials.

The North Cascade Range is part of the Coast Belt collisional orogen, extending from southeast Alaska to western Washington. The Straight Creek—Fraser fault (a major N-S strike-slip break) and several NW-trending fault zones divide the range into major tectonic blocks, within which the rocks, tectonic styles, and metamorphic facies are fairly consistent. The western North Cascades and San Juan Islands constitute a regional melange, a zone of dominantly NE-dipping, SW-vergent imbricate thrust sheets. Submarine and arc volcanic rocks and associated clastic deposits, variably metamorphosed, ranging in age from early Paleozoic (possibly Precambrian) through early Cretaceous, have been juxtaposed in a stack of at least four imbricate nappes and a probable autochthon, all of which have undergone subsequent vertical and transcurrent fault¬ing. Crystalline rocks of the Cascades core, having significantly different character and history, lie east of Straight Creek fault.

Thrusting, high-P metamorphism, and plutonic intrusion occurred in the Late Cretaceous (-100-80 Ma), during which plutonism, metamorphism, and deformation stitched the older terranes together. Widespread extension, translation, magmatism, and basin development during an Eocene event affected most of northwestern North America, including the Cascades orogen. The Oligocene to Holocene magmatic arc was superimposed on the whole package, and Pliocene to recent uplift and erosion brought the range to its current state.

The terranes west of the Straight Creek fault zone are divided into two major blocks by the NW- to WNW-trending Darrington-Devils Mountain fault zone (DDMfz), plus a melange belt within the fault zone. At the south end are the Western and Eastern Melange Belts (WEMB) of Mississippian(?) to lower Cretaceous rocks (including many low-P,T metamorphics). The Helena—Haystack melange (HHm) is a tectonic zone consisting of a wide variety of rocks in a serpentinite matrix. It is coincident with the DDMfz, a band of high-angle faults extending from E of Mount Vernon to a point SE of Darrington. Tabor (1994) believes that the HHm is a tectonic suture formed as the Northwest Cascades System was thrust over the WEMB; and that its assembly took place in the latest Cretaceous or early Tertiary (90-50 Ma), with subsequent strike-slip and dip-slip faulting.

The Northwest Cascades system (NWCS) comprises the blocks north and east of the DDMfz (including the San Juan Islands, not discussed here). The NWCS is a tectonically imbricated stack, consisting of several nappes and an autochthon (Tabor and others, 1994). From structurally lowest to highest, they include:

1) Harrison Lake terrane (autochthonous, mJr-eK): including Wells Creek Voles, Nooksack Grp.
-} Excelsior thrust
2) Excelsior nappe (Dev-Tr): including Chilliwack Grp, Cultus Fm.
-} Sumas Mountain thrust
3) Welker Peak nappe (Bell Pass melange, pDev?-K?): dominantly the Elbow Lake Fm (Brown and others, 1987), associated with a variety of smaller bodies, including Yellow Aster Complex, Twin Sisters Dunite and other ultramafics (e.g., on Sumas Mountain); parts(?) of the Vedder Complex; tonalite at Bowman Mountain.
-> Shuksan thrust
4) Shuksan nappe (Easton metamorphic suite): Jurassic submarine rocks that underwent early Cretaceous (pre-120 Ma) blueschist-facies (high-P, low-T) metamorphism:
a. Shuksan Greenschist (and blueschist): MORB-type submarine basalt protolith (with some arc component?);
b. Darrington Phyllite: sea-floor shale and minor sandstone protolith;
c. Semischist and phyllite of Mount Josephine.

Darrington Phyllite underlies the south half of the area we will traverse today; the semischist of Mount Josephine is exposed on Sumas Mountain.

Late Cretaceous erogenic activity (overthrusting, metamorphism, and calc-alkaline plutonism) extended into the Paleocene and Eocene epochs. The area of the Cascade Range was strongly modified by a poorly-understood Eocene tectonic event, during which all the major faults in the region experienced significant motion; the Straight Creek fault underwent post-mid-Cretaceous offset estimated at 80-190 km.

Eocene fluvial strata accumulated in rapidly subsiding basins in an active extensional strike-slip regime. Thick sections (up to 6000 m) of continental strata are found in several locations. Arkosic sandstone, silt-stone, conglomerate, and coal of the Chuckanut Formation crop out in one large tract across Whatcom County and several disconnected basins between Bellingham and Monte Cristo; these are probably remnants of a once-extensive fluvial deposit. The current outcrop area of Eocene sedimentary rocks in Whatcom, Skagit, and Snohomish counties is >3000 km2. Johnson (1991) identified six or seven members in the main belt, recording phases of deposition and/or deformation. To the south, sedimentary rocks included in the Barlow Pass, Swauk, and other Eocene units have long been recognized as preserved remnants of fluvial depositional basins. Evans and Ristow (1994) interpreted the southeastern belt rocks as showing an evolution from deposition in a broad basin (regional extension and subsidence), to progressive separation into smaller basins after the early-middle Eocene («50 Ma). The sandstones were strongly folded, on N- to NW-trending axes, by the late middle to late Eocene. Eocene K-Ar ages in the Cascades core record cooling by rapid unroofing of rocks that were deep and hot before the middle Eocene, implying uplift.

Later (Pliocene to present?) uplift along the N-S Cascades trend raised the North Cascades several thousand meters, while erosion exposed rocks from deep in the crust. Magmatic activity in the North Cascades has continued through the Neogene, as illustrated by a long history of volcanism in the Mount Baker area, from Kulshan caldera (Hildreth, 1996), to the Black Buttes, to the present cone. Eruptions and sector collapse from Mount Baker have continued into relatively recent times. A flank collapse on the Roman Wall sent a huge debris flow down the Middle Nooksack about 6600 years ago; a more modest lahar was triggered in 1891 (Hyde and Crandell, 1975, 1978; see Dragovich and others, 1978).

The geologic history and structure of the Cascades have great importance for current landforms. Figure 1 shows a digital shaded-relief map of the mountains of western Whatcom County. The orientations of rock units and faults affects ridge and valley forms and trends, such as the prominent N-S and NW-SE grain of the topography. The stratigraphic and structural juxtaposition of rock units influences the patterns of resistance to erosion, and thus the form of rock-based landforms. Resistant rock types (such as Eocene sandstones) stand highest in the landscape, holding up ridges and craggy peaks. Weaker types, such as some of the low-grade metamorphic rocks (e.g. phyllites) form lower mountains with gentler slopes, and some undergo gravitational sagging.

Quaternary Geology

Several periods of glaciation affected northwest Washington. The latest episode (Fraser glaciation) is the best understood, and had the greatest influence on present landforms, so is emphasized here (see Booth, 1987).

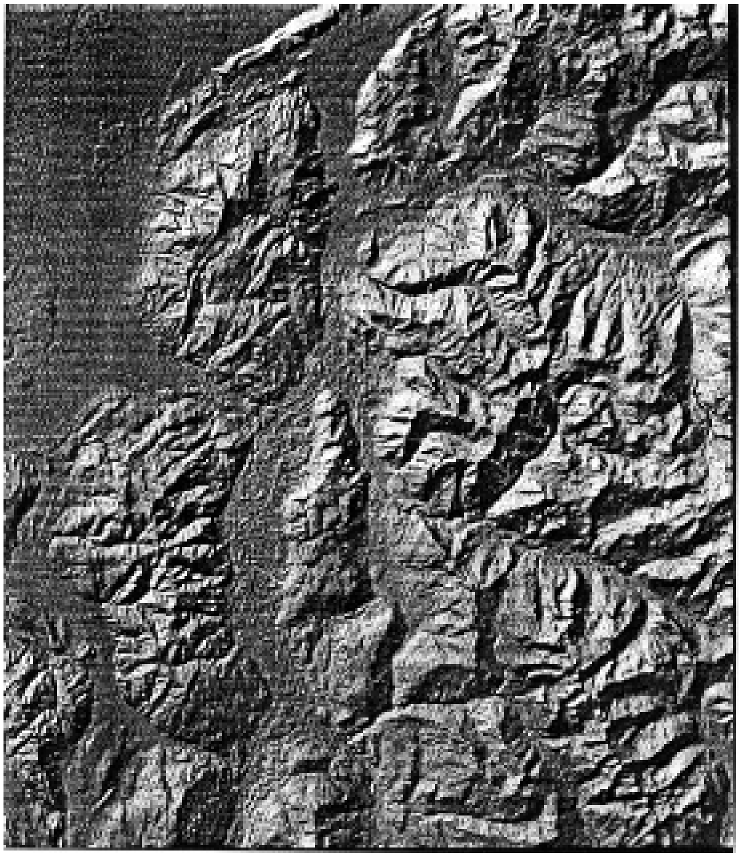


Figure 1. Shaded-relief image of part of western Whatcom County, from digital elevation data. Top of image at U.S.¬Canadian border (49 °N); bottom approx imates the Whatcom-Skagit county line. The Van Zandt Dike is left of center. (D.J. Miller, 1994)

Alpine glaciers expanded as global climate deteriorated after about 25 ka, until they reached their maximum extent about 18 ka and began to retreat. The Cordilleran ice sheet was growing in British Columbia at the same time. The Puget lobe built a platform of outwash sediment as it moved south, which remains as the great lowland fill (Booth, 1994). When the ice lobe spanned the distance between the Olympic and Cascade ranges, a proglacial lake was formed in the southern lowland; eventually the lacustrine sediments were over¬lain by prograding outwash. The region experienced maximum continental ice extent (Vashon stade) about 14-15 ka.

Along the Cascades, the character of the Puget lobe margin varied from north to south. To the south, alpine glaciers had retreated, and the continental ice extended up the valleys. The ice sheet inundated the mountains from the Skagit Valley north, at maximum glaciation, with only the highest peaks peeking out. But during ice advance and retreat, water ponded in the ice-free parts of the northern valleys, and lacustrine and outwash sediments were deposited in and around them. At their highest levels the lakes drained partly by passing around the ice and through gaps in the mountains, but mainly(?) by subglacial pathways, where outflow contributed to the erosion of the Puget lowland terrain (Booth and Hallet, 1993).

As continental ice wasted and then withdrew from the Puget basin, a sequence of glacial-margin channels and associated recessional-ourwash deposits formed in the valleys and along the mountain front. The terraces associated with this period are at successively lower elevations, graded to lower ice-sheet heights and the levels of proglacial lakes and ice-marginal streams. In the north, land that had been depressed by the weight of ice was drowned by the rise of sea level: water (and glacial-marine drift) extended to (present) elevations of «30 m near Everett, and up to «150 m near the Canadian border (Dethier and others, 1995). Only when the isostatic recovery of the land had exceeded the rate of sea-level rise did the shoreline and valley bottoms of the Puget lowland emerge above salt water. A late-Pleistocene readvance or still-stand of continental ice (the Sumas stade) affected the Nooksack-Fraser delta, and possibly valleys of the Nooksack forks as well (Kovanen and Easterbrook, 1996).

The period during and after the withdrawal of continental ice was a time of rapid erosion and sediment transport. During this so-called paraglacial period, valley-fill deposits were incised and excavated by streams as they reestablished their grades toward sea level across the loose, largely unvegetated landscape (Church and Ryder, 1972). The recently deglacierized hillslopes were also susceptible to rapid erosion, and mass wasting and surface erosion were probably significantly faster than before (under ice) or since (under vegetation). Some of the large landslides in the Cascades may have occurred during or immediately after deglaciation. In addition, eruptions of Glacier Peak (especially a major event about 11,250 years ago; Beget, 1981, 1983) and Mount Baker (Hyde and Crandell, 1975, 1978) sent large amounts of material as lahars down the Stillaguamish and Skagit valleys. The combination of paraglacial and volcanic sedimentation helped build the Skagit-Samish delta, filling around former islands that are now isolated hills in the flats.

Alpine glaciers were also active in the North Cascades throughout the Quaternary. Judging from present conditions, glaciers can exist on the highest peaks and in north-facing cirques even through interglacial periods; about 750 persist to this day. In colder intervals, alpine ice probably formed caps on the higher ridges and.extended into the valleys. Some advances of alpine ice probably also occurred during the Neoglacial periods of the Holocene, based on studies in the Snoqualmie, Yakima, and Wenatchee valleys, u-shaped valleys are found throughout the North Cascades.

The Lower Skagit Valley

Near Sedro-Woolley, -35 km from its mouth, the Skagit River passes from its E-W valley and into its delta. From high spots around town, one can see the flatlands extending more than 15 km west to Skagit Bay (see Figure 2). At the climax of Vashon glaciation, the top of the Cordilleran ice sheet was almost 1000 m above this point and extended east completely over the Cascade Range. In the lowlands to the west, under Whidbey and Camano Islands, Quaternary unconsolidated deposits (from multiple glacia-tions and interglacial intervals) reach thicknesses of w 1000 m. Since the last deglaciation, the Skagit delta complex was depos-

Figure 2. View west over the lower Skagit Valley and delta. (M.J. Brunengo, 1981)

ited into the Puget estuary (which was up to ~60-90 m deeper here for a while, until isostatic rebound), filling around several bedrock and till islands that are now the hills within the delta. To the south in the distance, the hills of Devils Mountain are underlain by Cretaceous and early Tertiary rocks. The structural grain of the several WNW-trending faults (the Devils Mountain fault zone) and subparallel folds is reflected in the linearity of the ridges and valleys across these hills. The weaker strata and fault zones were gouged by water and ice into prominent grooves, many of which hold lakes or wet¬lands. These structural and topographic trends persist west toward Fidalgo and the San Juan Islands; and east toward Lake Cavanaugh and the Stillaguamish basin.

The large massif SE is the Cultus Mountains. The west side is underlain mostly by Darrington Phyllite, the east side by slightly younger metaplutonic and metasedimentary rocks of the Helena-Haystack melange. It may be possible to see large landslides on the west side of Cultus: the most obvious is ~500 m wide and 450 m high. There are many such features on Cultus and Haystack mountains, most of them situated along fault contacts and/or incised stream valleys. Miller and others (1985) speculated that many of these landslides occurred shortly after deglaciation.

Just east of Cultus, the Day Creek valley is one of several NW-trending troughs holding late-glacial and re¬cessional sediments. It has a low divide (<500 m elevation), ~15 km south of the Skagit Valley, and it was probably a glacial-age overflow channel from the Skagit to Deer Creek and the North Stillaguamish. Day Lake, ~11 km up-valley, was impounded by a rockslide of Darrington Phyllite; radiocarbon dates of 1650 and 1850 (±50) yr BP from snags in the lake indicate that the slide occurred no more than «1650 years ago (Pringle and others, 1998). The village of Day Creek near the mouth is an old sawmill town as well as farming and logging area.

East of Day Creek, SW-dipping Chuckanut rocks are exposed around Cumberland Creek. This is the north end of a fault-bounded block in which a syncline has formed in the Tertiary sandstones, squeezed between blocks of Shuksan (E) and Darrington (W) rocks. The Skagit Cumberland Coal Co mine was located along the creek: five prospect runnels were driven into the hillside, but the mine apparently never reached production. Iron-ore prospects and claims lie in the metamorphic rocks east of the creek.

There are also small bodies of Chuckanut on the north side of the Skagit, at Bacus Hill and on the south edge of Lyman Hill (site of the Cokedale coal mine). Hamilton, on the north bank of the river, was settled in 1877; in the 1890s it was being touted as another Pittsburgh of the Pacific Slope because of the presence of coking coal (particularly from the Cokedale mine) and magnetite ore. Part of the town is being moved because of flood problems. Bacus Hill, to the NW, was the proposed site for the Skagit nuclear plant (Adair and others, 1989).

Lyman Hill, NE of Sedro-Woolley, is underlain by Darrington Phyllite (discussed later). Lyman Pass, bet¬ween Lyman Hill and Mount Josephine, is another NW-trending slot, probably fault controlled, through which ice and water flowed from the South Nooksack valley into the Skagit. Due north of town, there is a major gap between Lyman Hill and Anderson Mountain, to the west. We will be driving though that gap, through the upper Samish valley and into the South Nooksack.

History of Sedro-Woolley and Vicinity

This part of the Skagit Valley was being farmed by the 1870s. Growth of the town of Sedro (a misspelling ofcedro, Spanish for cedar; previously called Bug and Kellyville) was aided by the clearing of snags from the Skagit in 1879, making the river navigable by steamboats. Its sister community grew around a mill built by P.A. Woolley in 1891. The two villages officially merged in 1898.

The foothills and highlands were opened chiefly by loggers, first with hand saws and draft animals, later with steam tools and railroads. Dirt tracks were turned into railroads, and dozens of lumber, shingle, and tie mills were strung along the main railways. Logging locomotives climbed Devils Mountain and Cultus Mountain beginning in 1903, and the lower slopes were cut by the 1920s. The Skagit Mill Co sawmill (just E of Lyman) operated until 1936, and the railroads until 1938. Soundview Pulp Co succeeded Lyman Timber; by the time the show was sold to Scott Paper (the immediate predecessor of Crown Pacific) in 1951, most of the logging rails were gone from the hillsides. The higher slopes of the region were cut in the 1960-'70s, using chain-saws, trucks, and cable-yarding equipment, after the rail lines were abandoned (mostly in the late 1920s-'30s). Some of the low-elevation plantations are now being harvested again.

In its heyday around 1910, Sedro-Woolley had three sawmills, 10 shingle mills, eight logging camps, and a population of about 3000 (Erickson, 1994). The shell of the Skagit Steel & Iron Works plant, over the years a major manufacturer of logging equipment such as railroad locomotives, steam donkeys, saws and sawmill machinery, and yarding towers, lies at the curve of SR 20. The town was a crossroad for the railways of the region. The Seattle, Lake Shore & Eastern ran N-S; the Seattle & Northern, Fairhaven & Southern, and Puget Sound & Baker River railways all ran E-W in the valley; and many short logging railroads stretched from the hills to mills or log dumps (Thompson, 1989). Most of the major lines were eventually merged into the Northern Pacific, the Great Northern, or the Chicago, Milwaukee, St. Paul & Pacific (Milwaukee Road).

We will travel north on State Route 9, which extends from Bothell to Sumas, usually in N-S—trending structural and glacial valleys east of the central Puget lowlands. Although a secondary road now, the SR 9 route is one of the oldest roads in western Washington. By 1859 the military road linking Fort Steilacoom, Seattle, and Bellingham passed this way. The route was utilized by the Seattle, Lake Shore & Eastern Rail¬road (SLS&E), built in 1890-91; tracks can be seen in places along the highway (the old railroad bridge is next to the current highway bridge across the Skagit River). The SLS&E was acquired in 1897 by the Seattle & International Railroad (S&I), which in turn was controlled by and ultimately (1901) absorbed into the Northern Pacific as its main line into British Columbia. The N-P eventually merged into Burlington Northern, and recently into the Burlington Northern—Santa Fe; trains still run on this line. Parts of the road route were straightened and improved to act as an alternate (to US 99 and 1-5) N-S road in the 1960s, and some stretches are currently being expanded to handle increasing suburban traffic.

Road Log (in miles)

0.0 Intersection SR 20 and SR 9 (N), east edge of Sedro-Woolley; drive north on SR 9. You are climbing the scarp of an extensive glacial-drift terrace at 50-100 m, made of or mantled by till, outwash, and glacial-marine drift (see Dragovich and others, 1999, 2000). The rolling surface is pierced by bedrock knobs such as Butler Hill, and fragmented by postglacial incision in the cut made by the Samish River (both to the, west).

0.8 Northwest regional office of the Department of Natural Resources; maps and other information available during business hours.

1.4 As the road turns slightly to the NE, get a view of the southwest (Hansen Creek) side of Lyman Hill (Darrington Phyllite, mantled with till in places).

3.0 Attain the highest level on the terrace («100 m). A proglacial lake dammed by glaciers in the Nooksack trough probably spilled south through this gap; marine water rose slightly above this elevation and extended through the gap while this area was isostatically depressed at the end of the Fraser glaciation. Anderson Mountain (phyllite) to the left.

4.5 Driving north, you get a better view of the valley between Anderson Mountain and Lyman Hill (on the south edge of Fig. 1, left of center). This is one of several N-S valleys that separate large blocks of Darrington Phyllite; others include the troughs occupied by Lyman Pass and the south ends of Lake Whatcom and Samish Lake. These breaks were undoubtedly expanded by glacial scour, subglacial flow, and fluvial action by outwash streams, but the ultimate reasons for their existence are unclear. Until recently, no one(?) had mapped any structures through the valleys, probably because the rocks give too few clues for proper stratigraphic identification of faults or folds. Dragovich and others (1999) mapped a concealed fault through this gap.

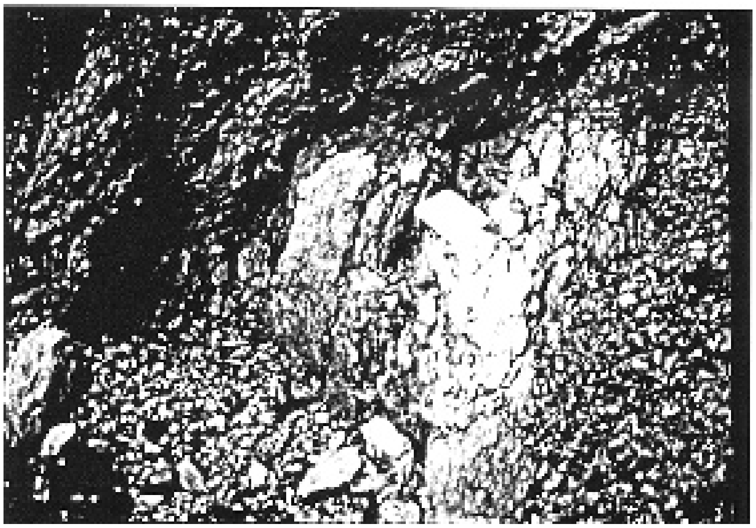
Intermediate-grade metamorphic rocks constitute one of the widespread bad-actor units of the North Cascades. Darrington Phyllite (quartzose graphitic phyllite, with sericite, albite, muscovite, and chlorite; named for Darrington, in Shohomish County) is one of the most common, underlying most of the western hills between the Skagit and the Middle Nooksack. It is foliated, fissile, and jointed (Figure 3), and all of these discontinuities contribute to a general weakness that makes the rock susceptible to mass movement. Slopes underlain by phyllite fail by slump-earthflow, sackung, and slow rotation of individual blocks within a soil matrix (Thorsen, 1989). In general, these weaker rocks cannot hold high-relief slopes, and form more subdued topography than the stronger Chuckanut sandstones and some of the other pre-Tertiary rocks. The soils tend to be clayey, cohesive, and poorly permeable, so slopes have developed dense drainage networks; roads built on them must contend with high runoff rates and the possibility of gullying.

Anderson Mountain and Lyman Hill are the sites of many sackung features (described by Thorsen, 1989), partly because they are bounded by broad structural-glacial valleys. As the combination of glacial and fluvial erosion removes material from their sides, the mechanically weak phyllite mountains sag toward the valleys. Identifiable features include bulging lower slopes, anti-slope scarps, and longitudinal cracks; there are many discontinuous troughs and uphill-facing scarps in the summit ridge of Lyman Hill (Figures 4 and 5). These materials also seem to have a penchant for large earthflows. Although the erosion that triggered the sagging may occur mostly during glacial episodes, the mass-erosion processes persist to the present (although the relative rates are unknown).

5.6 As the bench narrows, the road drops over the scarp toward the Samish Valley bottom.

5.9 Cross the railroad tracks (the old SLS&E route again).

6.2 After driving north parallel to the tracks for about 0.3 mi, the highway veers NW around the alluvial fan built by Thunder Creek. The creek deposited the cone across the glacial bench, then incised it; the secondary fan on the valley floor has deflected the Samish River to the west, and helped form the ponded wetlands upstream.



6.6 Samish River bridge. Most of the community of Prairie is located on the fan, which is out of the floodplain and thus relatively dry; the exposure to other hazards (debris flows) has been less apparent in the past.

7.3 On the west side of the valley, the road rises and falls across several debris/alluvial fans. Note the clusters of farm buildings on each fan, and the small creeks that built them (although they are about 2-3 km long and fall 900 m).

A minor disaster occurred on the SE slopes of Anderson Mountain on 10 Jan 1923 (60 years to the day be¬fore a more recent episode). Three men were bringing a locomotive back from repairs in Sedro-Woolley. After leaving the main N-P line north of here, they were climbing toward the McCuish Logging Co camp in the pre-dawn darkness, and failed to notice that heavy rains and flows had washed out a long section of trestle. All three were killed in the 30-m fall.

7.6 Mills Creek, in view briefly on the opposite side of the valley, provides an illustration of the problems of less-obvious and infrequent geologic hazards.

After a week of heavy rain and snowmelt, an intense downpour on the night of 10-11 January 1983 triggered about two dozen debris torrents in western Whatcom and Skagit counties early on the 11th (Gerstel and Bru-nengo, 1994). Here, the buildings of the Hofmann veal farm were located on a low alluvial fan, out of the boggy soils of the Samish floodplain. However, a small landslide involving the fill of an orphaned forest road turned into a debris flow that scoured its way -2.5 km downstream and blew through the farm, killing Hans Hofrnann (the only human fatality that day) and about 200 calves. Figure 6 shows the path and deposit of the 1983 debris flow. Another torrent flowed down Mills Creek the following winter, causing more damage to the remaining buildings.

Such processes had occurred in the region before; a lawsuit stemming from a 1979 torrent in Sygitowicz Creek (a

Figure3. (top) Exposure of Darrington Phyllite, on Lyman Hill. (M. J. Brunengo, 1983)
Figure 4. (middle) Sackung features in phyllite: linear trough and uphill-facing scarp, near the top of Lyman Hill. (M. J. Brunengo, 1984)
Figure 5. (bottom)Sackung features in phyllite: pond in linear trough, summit ridge of Lyman Hill. (M. J. Brunengo, 1984)

Figure 6. Track and deposit of the Mills Creek debris flow of 11 Jan 1983: source on Lyman Hill, flowed to Samish River (bottom); damage to Hofmann farm buildings. (Copyright R.R. Geppert, 1983)

tributary of the South Nooksack, discussed later) was in process when the 1983 storm occurred. Of course, many other lawsuits followed the 1983 storm (ask GWT and MJB). But the 1983 events spurred the beginning of some changes (although they took years) in hazard evaluation, forest-practices regulation, land-use planning, and road engineering.

10.4 The former mill town of Wickersham was also built on a fan. It was site of the junction between the Northern Pacific (previously SLS&E) railway line in the valley and the N-P's route to Lake Whatcom and Bellingham.
If it is clear, the craggy, glaciated Twin Sisters, capping one of the largest dunite bodies in the world, may be visible at 2 o'clock.

10.9 Junction with Park Rd, leading to Lake Whatcom. The road and railroad (now a tourist line) pass through a narrow E-W gap between Anderson (S) and Stewart (N) mountains.
In times past, lumber and coal were the prime products of this area. In the 1910s-'20s, the Wood-Knight Lumber Co mill stood at South Bay of Lake Whatcom, and there was a logging camp at Park. The Blue Canyon coal mine, at the SE end of the lake, operated from 1891-1919. It was the second most productive mine in the coal belt of Whatcom and Skagit counties (*250,000 metric t), and gave its name to the Blue Canyon coal zone (base of the Chuckanut). An explosion in 1894 killed 23 men, the worst mine disaster in state history. Although farming and timber production remain important land uses, recreational homes and the expanding suburbs now occupy much of the lower ground, especially by the lakes.

Bellingham's water supply also passes through this gap. Water is diverted from the Middle Fork Nooksack into a 17-km aqueduct (buried most of the way). The pipe ends at Mirror Lake, just west of here, where sediment is allowed to settle. The water then passes into and through Lake Whatcom and is collected at the far end. There are concerns over sediment from logging in the lake's basin, as well as pollution from septic systems contributed by the basin's growing population.

11.1 On a fine day, you can view to the right (E) the north end of Lyman Hill, the wide valley between Lyman and Blue Mountain, the craggy Twin Sisters, and the top of Mount Baker.

12.9 Saxon Rd. These flats form an indistinct divide between the Samish and Nooksack drainage basins. A small ditch to the east is either the head of the Samish (as on the 1:100,000 map and streams catalogue), or flows north to the South Nooksack (as on the 7.5-minute topographic map).

The divides probably shift around, as floods and deposition alter the loyalties of the small streams; ditching of farm fields has probably contributed to the changes. This may be an important issue, however, to anadromous fish: a salmon trying to return to a natal stream around here might have to choose between river mouths that are 25 km apart, and a run 45 km up the Samish or 78 km up the Nooksack. Since returning fish key onto the scent of a stream and the main stem into which it flows, it is unlikely that a Nooksack fish would find the scent should its tributary be diverted into the Samish (or vice versa) due to natural or man-made diversion. The end result would probably be a drop in salmonid production in the pirated stream, until enough straying occurs to reseed it. The South Nooksack River flows into the trough from the southeast. This segment is about 20 km upstream from the confluence with the north fork. The uppermost basin is underlain by dunite and other old rocks,but the reach immediately upstream has incised through phyllite hills. The river flows alternately on valley floors partly filled with drift and alluvium, and through narrow slots between the hills and/or terraces.

Gold was discovered in this river in 1860; by 1885, several hundred prospectors lived in the town of Livewood, near the mouth of Skookum Creek. Bloedel-Donovan Lumber Mills purchased much of the area in 1920, and logged until about 1941. Their main rail line along the river led to >80 km of track up on the benchy phyllite slopes between Skookum Creek and the upper South Nooksack. Sediment originating from landslides and logging roads on the erodible soils produces high turbidity levels during the rainy months, and contributes to degradation of fish habitat.

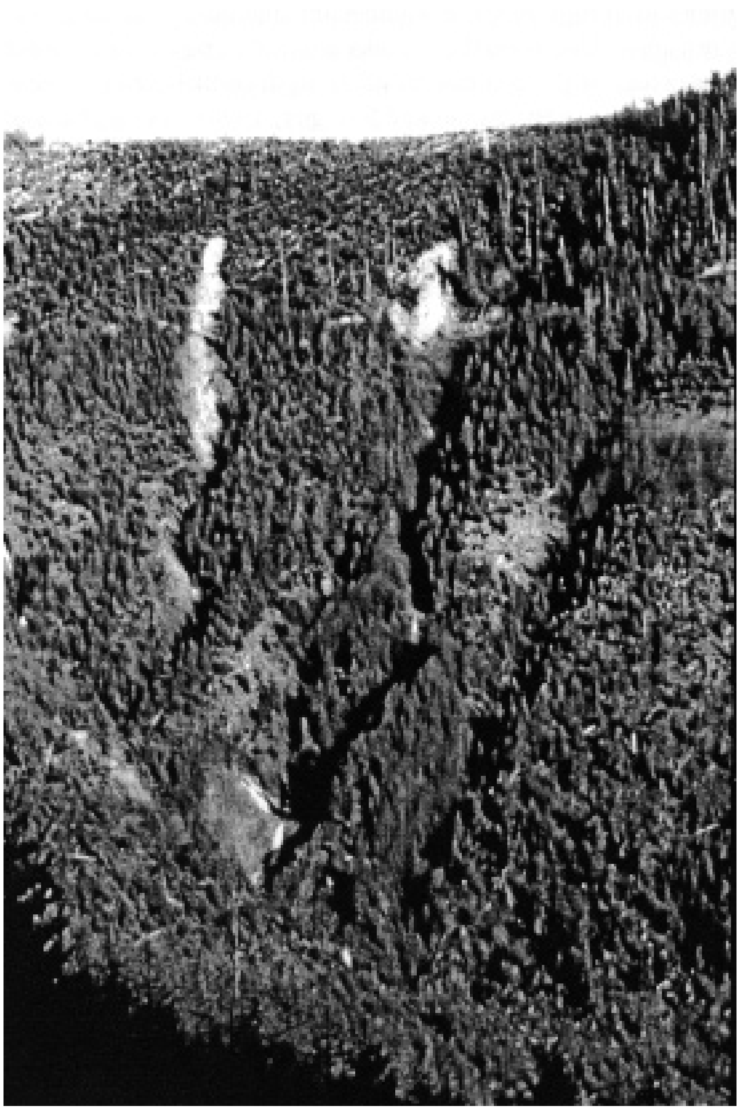
13.8 Outcrops of Darrington Phyllite exposed in cuts on the left (W) side of the road, part of the south end of Stewart Mountain.

13.8 Entering Acme, former site of a sawmill and a shingle mill, built on the fan of Jones Creek. You are at the base of Stewart Mountain; the contact between phyllite and the overlying sandstone angles down to the north, crossing the middle of the Jones Creek basin. (We will discuss the stability characteristics of Chuckanut rocks a bit later.) Jones Creek was struck by debris torrents in January 1983 and twice in November 1990.

Slightly north is the basin of McCarty Creek. The phyllite-sandstone contact intersects the valley floor there, and the McCarty basin is underlain by the sandstone and related sedimentary rocks of the Chuckanut Formation. This creek also experienced debris flows in January 1983 and November 1990. Evidence of torrent passage in the channel includes logjams, run-ups at channel bends, broad channel deposits, and nested terraces. A large landslide occurred in sandstone on the south slopes, probably during the 1990 storms. The landslide formed a dam, blocking the creek and impounding water and sediment. Fortunately for downstream residents, McCarty Creek was able to incise through the deposit along the left bank, prior to (potentially catastrophic) failure of the dam and generation of a dam-break flood.

15.3 Slow down as you cross the South Nooksack River; turn right onto Mosquito Lake Rd just past the bridge.

16.0 After crossing the valley floor, you begin to rise into the hills, through the gap between Blue Mountain and Van Zandt Dike. On Figure 1, the Dike is the crudely arrowhead-shaped body (pointing north) near the center of the map.
J.M. Van Zandt homesteaded west of the Dike in 1883; a post office was established there and given his name in 1892. The designation of the ridge as a "dike" is curious: it may have been so named because it seems to be a high barrier, blocking the rivers flowing west. (Perhaps the presence of Dutch and German settlers in the area had something to do with the name.) The Dike was first harvested beginning in the late 1800s, using steam donkeys and railroads. At one time logging supported five large mills in the South Nooksack valley between Acme and Deming. A fire in 1915 burned much of the forest (especially the north end), as well as several homesteads.



17.2 Turn left onto the gravel road, entering the Van Zandt block of state land (8560 ac), managed for timber production by the state Department of Natural Resources, under the Van Zandt block plan (WDNR, 1992).

19.5 Turn off to the left on a logging spur, in a recent clearing with good views to the west. Near here (about at Tinling Creek), the road crosses the contact between phyllite (below and S) and sandstone (N).

Stop 1. Slope processes in terrestrial sedimentary rocks.

Fluvially-deposited feld-spathic sandstones (with lesser conglomerates, siltstones, and coal) of the Chuckanut Formation are preserved in a broad area extending from Bellingham Bay to Mount Baker. (The name was applied by Capt Henry Roeder in 1852 to Chuckanut Bay; it apparently means "long beach far from a narrow entrance" [Hitchman, 1985].) The Dike is underlain by N- to NW-dipping strata of the Bellingham Bay member of Johnson (1985, 1991). Across the valley to the west, the north part of Stewart Mountain is made of Bellingham Bay and Padden member rocks (see Dragovich and others, 1997); the "Slide Mountain" massif to the northeast (visible from the next stop) is also Chuckanut Formation.

The Chuckanut and related rocks are relatively strong, and typically form prominent ridges and steep slopes. (Glacial scour during the ice ages was responsible for some of the

Figure 7. Debris slides—flows on slopes above Sygitowicz Creek: from 1979 and/or 1983 storm. (Copyright R.R. Geppert, 1983)

Figure 8. Track and deposit of the Sygitowicz Creek debris flow of 11 Jan 1983: source on Stewart Mountain, flowed to South Nooksack River (bottom). (Copyright R.R. Geppert, 1983)

relief.) But they weather into sandy, low-cohesion soils with little internal strength, and storm-water tends to perch on the soil-bedrock surfaces. As a result of the combination of high relief, low cohesion, and abrupt strength and ground-water boundaries at the soil-rock interface, slopes on these rocks are highly susceptible to debris slides and flows. Harvesting of trees causes loss of the component of strength contributed by tree roots, which can be critical on marginally stable slopes (see Buchanan and Savigny, 1990). The attitude of bedding planes and joint surfaces also partly controls mass-movement processes. Discontinuities in the rock, whether sandstone-shale contacts or joint openings, are major strength boundaries. Thus, the strength avail¬able to resist downslope stress varies depending on the orientation and steepness of the discontinuities. Soil and rock slides are more likely where the beds dip steeply parallel to the slope (dip-slopes); slab failures are relatively common in these rocks. On slopes crossing the beds (scarp-slopes and ribbed slopes, in the term of Fiksdal and Brunengo, 1981), debris slides also occur, but rock slides are apparently less common. Erosion by stream or wave action (or ice, during glaciations) can cause oversteepening, in which beds day¬light out of the slope; excavation for roads or buildings can have the same effect. Because of their manifest tendencies to cause trouble, slopes in terrestrial sandstones are often accorded special attention in planning and regulation.

The valley of Sygitowicz Creek is directly west, on Stewart Mountain. Several slides on the steep tributary slopes caused a debris flow in January 1979, which damaged the Sygitowicz house, located near where the creek flowed out of the mountains. While a lawsuit over that event was in progress, the January 1983 storm caused further sliding and another debris flow. Figure 7 shows some of the slides; Figure 8 illustrates deposition across the gentle fan and floodplain, to the South Nooksack. Hundreds of individual landslides in that event fed torrents in at least 10 streams on Stewart Mountain, damaging several homes in the South Nooksack Valley and along Lake Whatcom.

Rocks of the Chuckanut Formation are also susceptible to huge landslides, possibly as a result of seismic shaking; this subject will be discussed in the next few stops.

21.0 Stockpile of phyllite boulders and dirt, near a junction (stay right). The materials are from the DNR's McCoy Grade Pit, on the west side of Bowman Mountain (across the valley to the ESE). You may note that much of the road material on the Dike is phyllitic.

21.1 Stay left on road DE-N-1000, as the more heavily-traveled DE-N-1600 swings to the right. Note the irregular topography, with small wetlands in places.

22.7 New spur roads to the right and left; continue straight.

23.0 Entering newer cuts on the left; note the lumpy topography.

23.3 Approaching a blocked spur road on the left - park at the junction, or in wide spots to the south on the right. (The end of the main road is ~0.3 mi north; it's possible to turn around there.)

Stop 2. Van Zandt Dike landslide. This will be the starting point for a walk to the edge of the Van Zandt Dike landslide; those who wish to will walk down to the bottom, where the vans will pick us up. Take appropriate clothes, water, etc. for a hike of ~2-5 km, with a drop of -500 m.

Figure 9 is a topographic map of the area, with geologic mapping by Mary Raines, who studied the slide for a thesis at Western Washington University; Figure 10 shows sections across the slide and the valley. We are located near the end of the old road in the south part of section 10 (T 38 N, R 5 E), toward the north end of the relatively flat top of the Van Zandt Dike. Some of the older timber stands in sec 10 (and down on the western face) are survivors of the 1915 fire, while others (the tight dog-hair) grew afterward.

The DNR began trying to harvest trees in this part of the Dike in about 1985. In 1986-87, Jerry Thorsen was assigned to evaluate the geologic, geomorphic, and stability characteristics of the Dike Dish sale area. His sketched drawing and section are included as Figures 11 and 12. No one was proposing harvest on the scarp face, but there was concern (among the neighbors at the bottom, especially) that logging on the plateau might cause hydrologic or strength changes that could contribute to instability on the steep slopes. This effort eventually led to landform mapping and instability-hazard rating for the entire Van Zandt block (WDNR, 1992). (A more detailed map of the slide will be examined on the site, and we will discuss the possible relationships between timber harvest and slope instability on the slopes.) Ultimately, the block plan began to be implemented in the late 1990s; the area here and to the west (Thousand Dishes unit 1) was cut in 1997 or 1998. Climb over the multiple tank-traps and head west on the cat-road. It takes about 10 minutes to walk generally westward toward the edge of the Dike (~1 km; stay left at a couple of junctions). From the end of a track (next to a large slash pile), cut across to the treeline (by the low knoll, above the area marked Devil's Slide on the map). While walking, you might get a view of the mountains to the northeast, or even Mount Baker.

Note the terrain of the top of the Dike. Although pretty flat for the North Cascades, there are some interesting features up here. There are a series of discontinuous, NNW-SSE—trending low ridges, separated by shallow swales (some with boggy bottoms), rising generally to the NW. These seem to reflect the edges of NW-striking beds within the Chuckanut, where weaker layers were preferentially scoured out by glacial ice, leaving the more resistant strata standing out. Features such as these are quite prominent in other places in the region, especially on Chuckanut Mountain. Fiksdal and Brunengo (1981) called similar landforms on Slide Mountain (to the ME) "Chuckanut ribbed slopes" (in contrast to dip-slopes and scarp-slopes).

As you approach the western edge, look for collapse features (initially subtle, becoming decidedly not-so-subtle). At the face, we should be near the right end of the sketch (Fig. 11). We will turn right (N) and walk along the edge for ~0.5 km, to the bight in the edge west of the next knoll.
Figure 13 is a photo of the Van Zandt Dike and landslide from the west. The NW corner of the Dike collapsed toward the South Nooksack valley, sometime since the last glaciation. The scarp is ~5 km long and the deposit covers «15 km2. Except for the mapping of Thorsen and Raines, the slide has not yet been studied in great detail. Its age and dynamics are speculative, although hummocky deposits and blocks of far-traveled debris suggest catastrophic initiation and rapid movement (sturzstrom?), perhaps triggered by an earthquake. It is not even known whether the landslide dammed the Nooksack, but it seems likely. The orientation of the sandstone layers, and their interbed and joint discontinuities, probably affected the strength of the materials along the free face left by erosion. Two faults apparently intercept the northwestern corner of the Dike (see Dragovich and others, 1997), and these may have contributed by weakening some of the rocks.

As you approach the western edge, look for collapse features (initially subtle, becoming decidedly not-so-subtle). At the face, we should be near the right end of the sketch (Fig. 11). We will turn right (N) and walk along the edge for -0.5 km, to the bight in the edge west of the next knoll.

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The headwall is now a complex feature, involving sagging, slab failure, rockfall, earthflow, and debris sliding (see Fig. 11 and 12). Figures 14, 15, and 16 show some of the ground disruption around the top of the landslide scarp; Figure 17 illustrates the effect on an ill-positioned tree (a natural strain-gauge?). Minor (relatively) bluffs, uphill-facing scarps, benches, and large cracks are exposed on the slopes, among earthflows, talus deposits, and slide tracks (of various ages and activity) (see Fig. 11 and 12).

It is possible to get some appreciation for the activity occurring along this slope in a walk of about 2 km north along the edge, to the earthflow (large indentation in the NW corner of section 10). To see all of the features illustrated on the sketch and cross-section takes several hours. Most of us will hike down across the upper scarps and slopes, ending at the dirt road near the Vollmer home (east of the center of section 9).

In the context of forest management, this landslide suggests

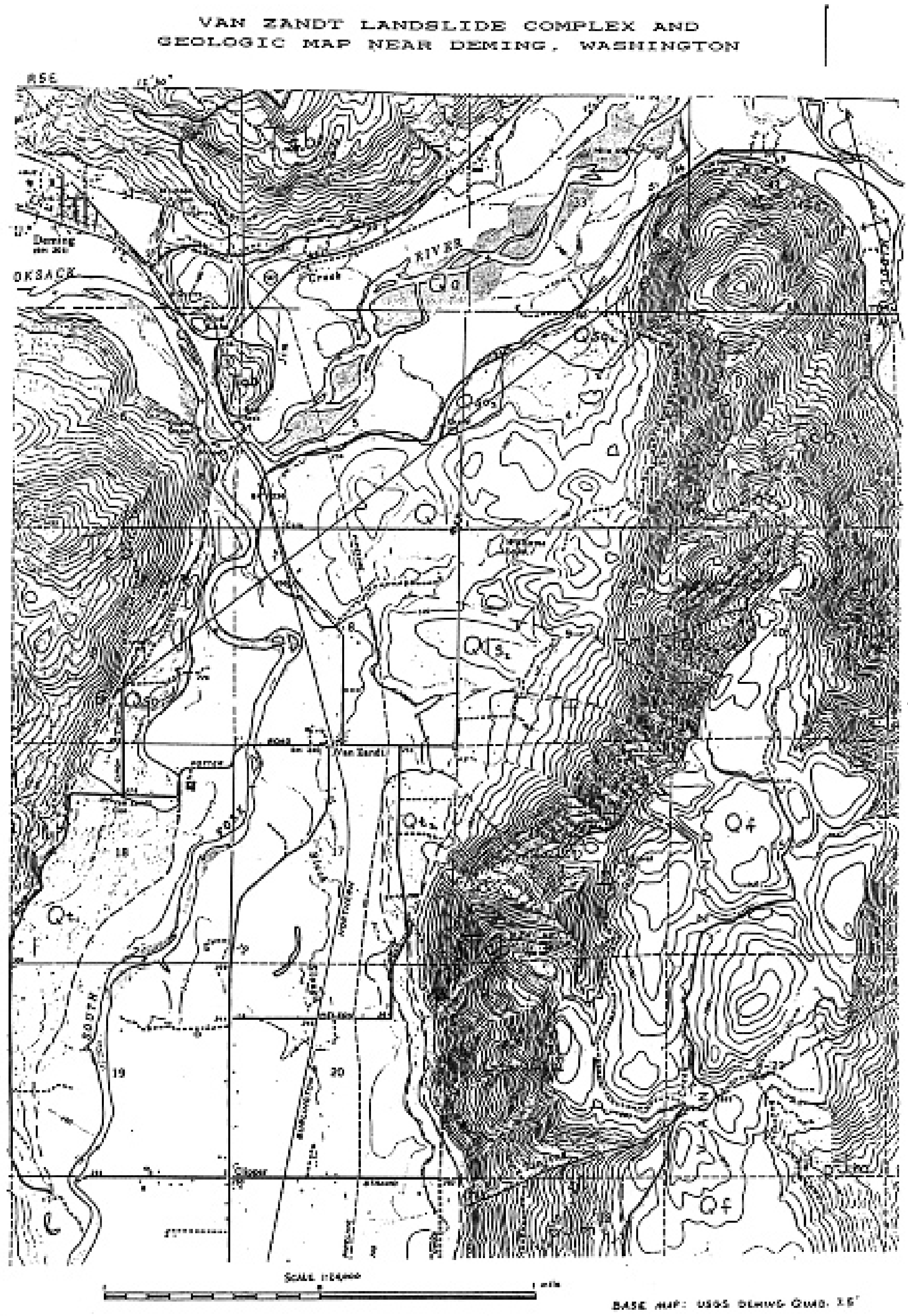

Figure 9. Van Zandt landslide complex and geologic map, near Deming, Washington; on USGS Deming 7.5 minute quad. (M.A. Raines)

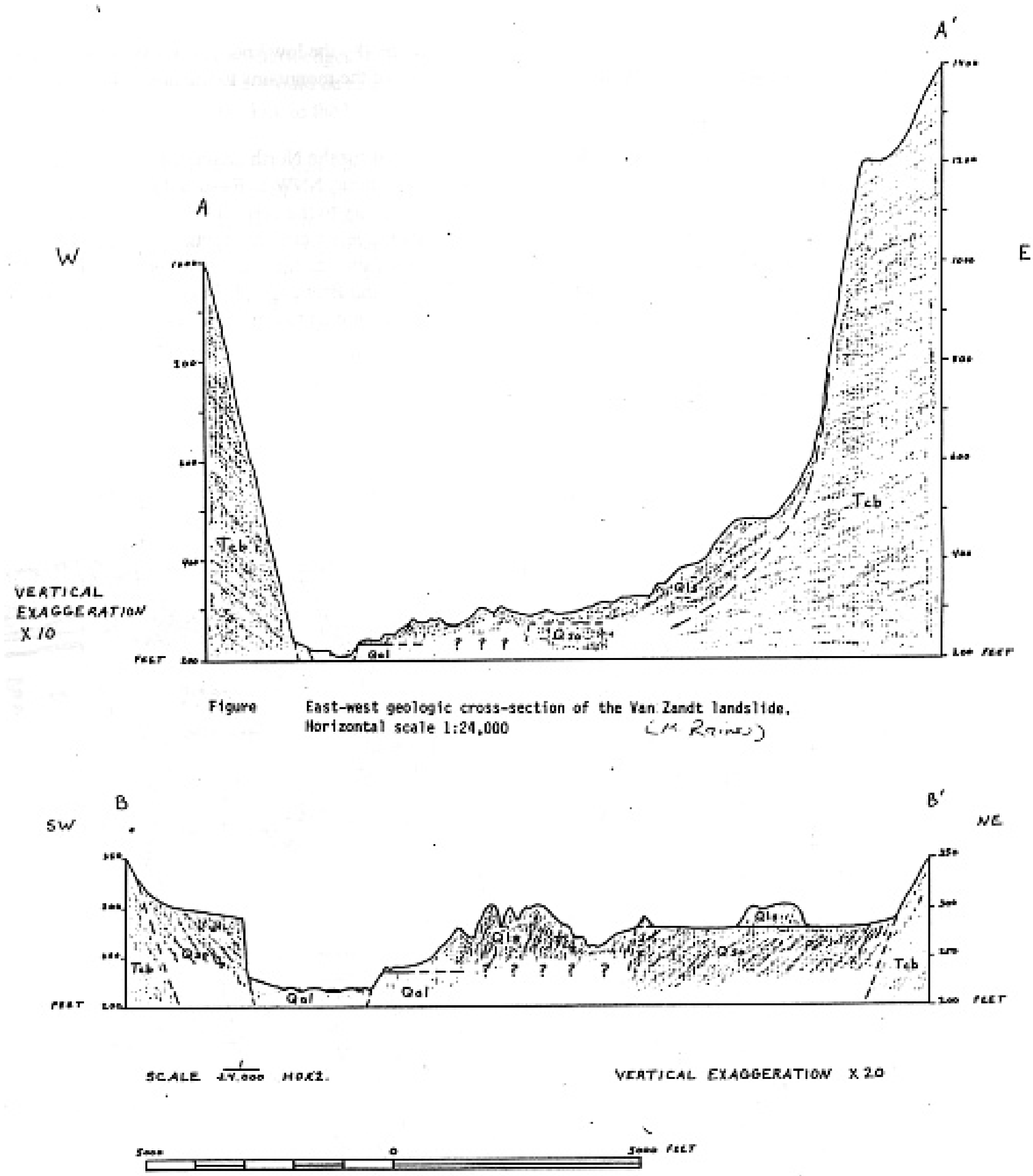

Figure 10. Cross-section of the Van Zandt landslide: A-A' (east-west, top), and B-B' (SW-NE, bottom); see Fig. 9 for section locations. (M.A. Raines)

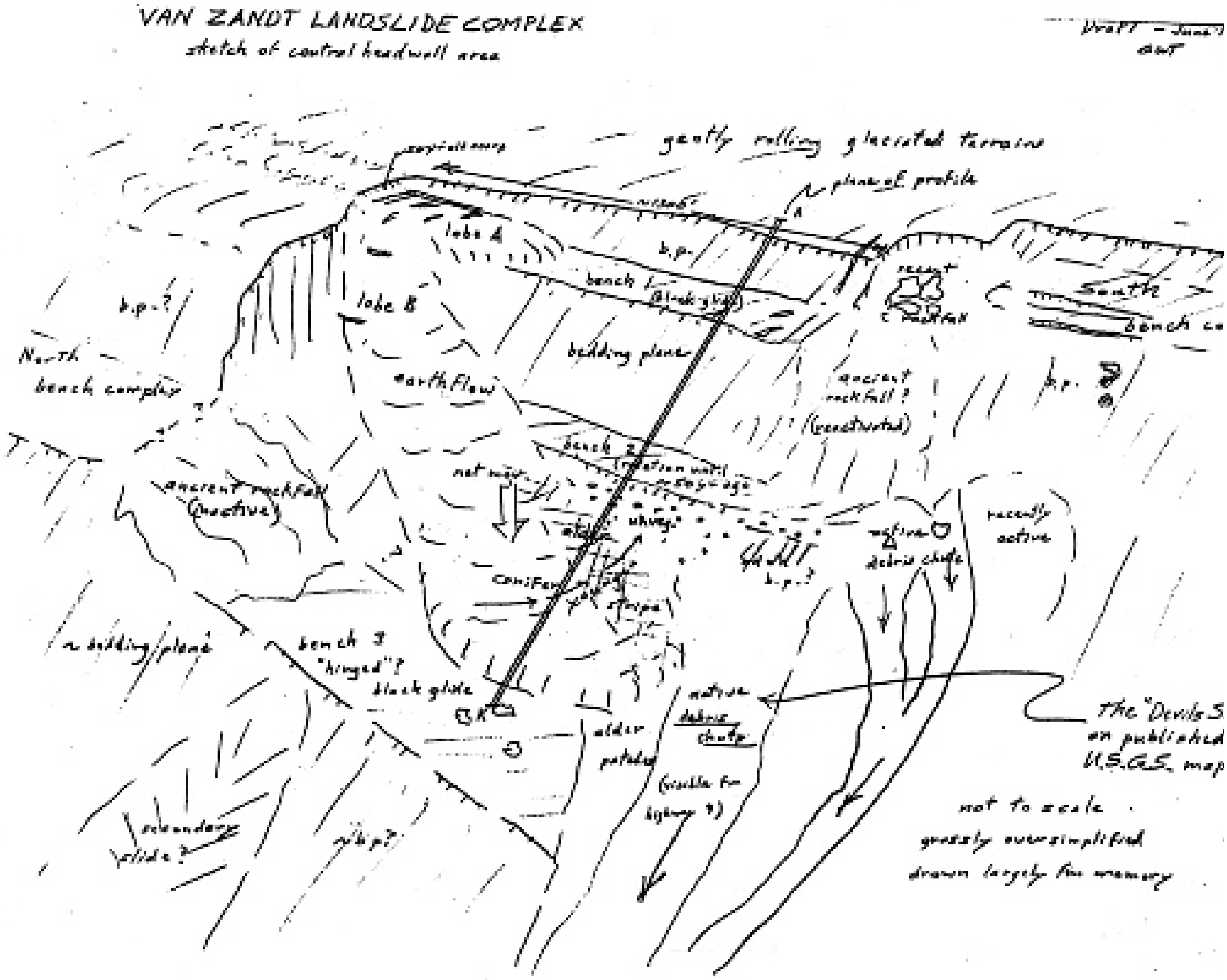

Figure 11. Van Zandt landslide complex: oblique field sketch of central headwall area. (G.W. Thorsen, 1987)

several questions and issues. If you were asked about management of this slope, how would you respond? Would it be all right to cut these trees? Do root strength or hillslope hydrology have anything to do with these huge slides? There are old cat-tracks and stumps around - parts of this slope have been logged before, and most of it burned in 1915. Did past cutting have any effects? Would harvest aid fire prevention, and thus reduce the possibility of subsequent erosion? What is the hazard level for buildings below?

If returning to the vehicles, walk back to the east (as long as you haven't gone too far north, almost any route east will intercept either a road or the old skid trail.)

The road log continues, for those driving to the pick-up point.

25.2 Junction with road DE-N-1600.

25.3 Rock-pile junction; stay left.

26.8 Spur on right with good views to the west.

29.1 Junction with Mosquito Lake Rd; turn right (W). Drive back down across the South Nooksack valley.

30.8 Junction with SR 9; turn right (N).

33.0 As you drive north, you get views of Stewart Mountain (W), the Van Zandt Dike (E), and Sumas Mountain (ahead). The south side of Sumas (in view) is underlain by folded and faulted Chuckanut sedimentary rocks, with several landslides. On the north and west sides, metamorphic rocks of the Excelsior and Welker Peak nappes are exposed, beneath discontinuous mantles of Tertiary sediments and glacial drift (Tabor and others, 1994; see Dragovich and others, 1997)
.

35.0 Begin to see the scarp of the Van Zandt Dike landslide, including patches of bare rock.

As the highway swings to the right (entering the town of Van Zandt), cross Black Slough, a parallel side-channel of the South Nooksack that collects drainage from the Dike face (from Tinling Creek north) and back-terrace wetlands of the

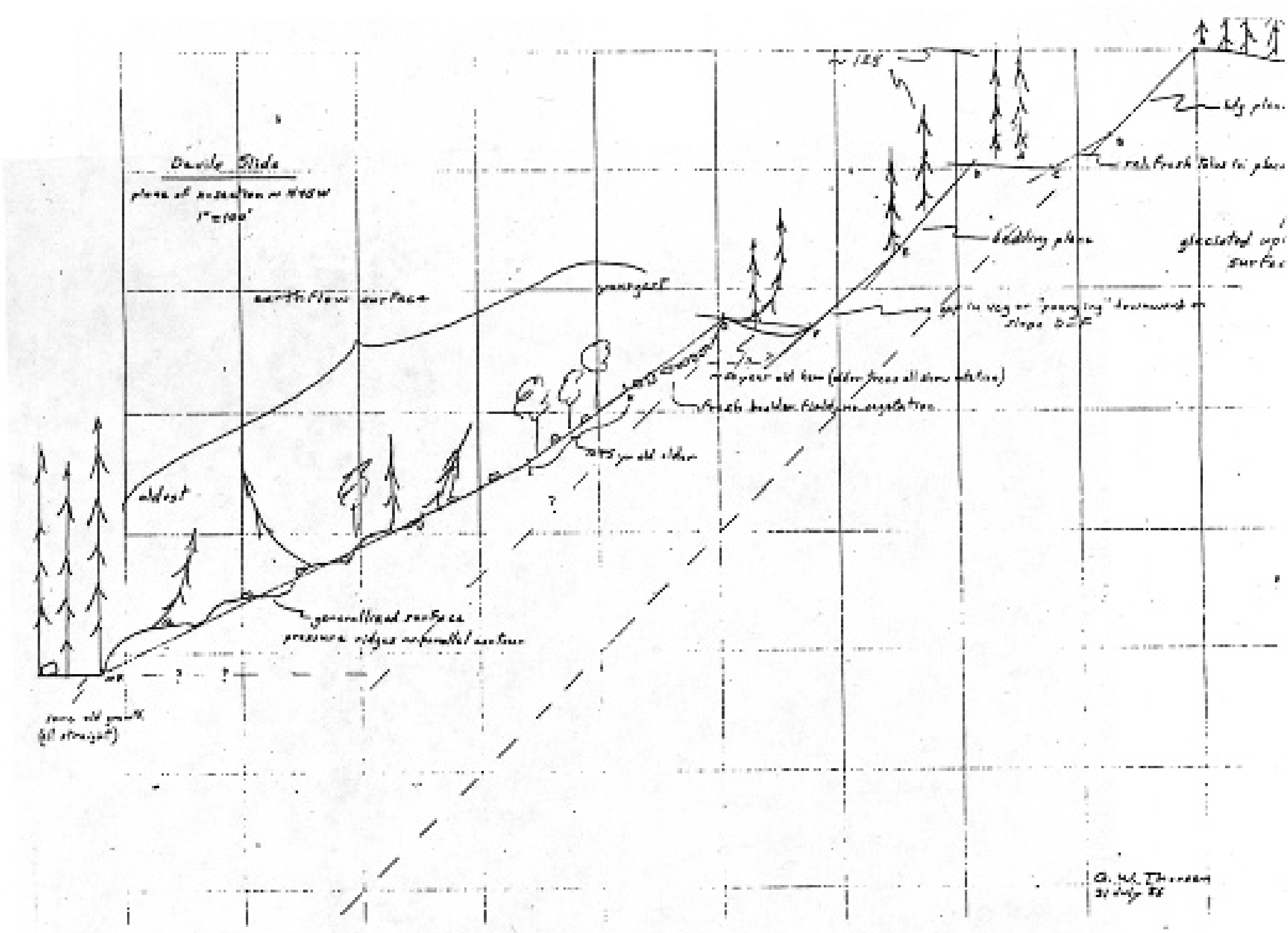

Figure 12. Van Zandt landslide complex: field section (see Fig. 11 for location). (G.W. Thorsen, 1986)

floodplain. Streams like this are typically valuable fish habitat, if not too damaged by sedimentation or channelization.

35.5
Just past the Van Zandt Store and the railroad tracks, turn right on Potter Rd (around a barricade) and drive uphill (east) 0.6 mi to a T-junction at Linnell Rd. Turn left (N); then, in 0.1 mi, turn right (E) up Schorn Rd. In about 0.2 mi, the pavement ends; follow the gravel road that goes to the left (N). In about 0.4 mi, there is a Y-junction, with a horse pasture and barn ahead - take the right fork. Drive another 0.3 mi (generally uphill), to where the Vollmers' driveway goes right; park in the overgrown dirt road on the left.

37.1
Stop 3. Middle of the Van Zandt Dike landslide. The Vollmers have kindly given us permis¬sion to pick up the NWGS hikers here. If not on an organized trip, please respect their property. The Vollmer property abuts the state-owned Van Zandt block to the east. Sneaking across the property line is a bulge (about 400 m long by 200 m wide) mapped by Thorsen as a slump-earth-flow. He noted that the last local adjustments seemed to have occurred in the 1940s, but steeper slopes uphill were freshly exposed as recently as 1975.

Return to the vehicles, and retrace the route (dirt road, Schom Rd, Linnell Rd, Potter Rd) back down the hill.

37.4 At the first junction (Clendenen place), a debris flow came through on 15 December 1999; its source was up on the face, just inside the SW corner of section 10 (N. Wolff and J. Grizzell, WDNR, pers. comm.). The torrent apparently jumped a bend in the channel, and flowed out through the horse-pasture. Although the horse has not offered an opinion, the human residents were pretty concerned.

As you go down the hill, note the topography in this area (see also Fig. 9): parts are hummocky (original landslide?), and parts are smoother (subsequent deposits of talus from rock-falls, debris fans, alluvium, other processes?).

39.1 Junction with SR 9 in the community of Van Zandt. The parking lot of the old store on the west side of the highway is a good spot from which to appreciate the southern part of the landslide scarp (perhaps while enjoying some post-hike refreshments).
When the time is right - turn north onto SR 9. The highway goes north (along the quarter-section line), on low floodplain that seems to be ponded behind the landslide (see Fig. 9).

Figure 13. Oblique aerial view (to the east) of the Van Zandt Dike, landslide complex, and Nooksack River; Mount Baker and Twin Sisters on the horizon. (P.T. Pringle)

Figure 14. VZD landslide headwall area: ground cracks. (MJ. Brunengo, 1993?)

Figure 15. VZD landslide headwall area: ground cracks. (M.J. Brunengo, 1993?)

Figure 16. VZD land¬slide headwall area: ground cracks. (P. T. Pringle, 1995)

39.6 Just past where the highway turns to the NW, rum right onto a gravel road (heading NE). Rise onto the edge of the landslide deposit: note that the terrain here is rather hummocky, with small marshes in the low spots.

39.8 Stop near the Olympic Pipe Line crossing; park in the best spot available.

Stop 4. Hummocky deposit of VZD landslide. The gravel road has been cut along the edge of a hummock. Take a few minutes to check out the characteristics of the material (is it a diamicton? sandstone boulders? what's the matrix?). Continue driving east ~0.25 mi to a turn-around point in a driveway; return west to the highway.

40.5 Turn right (NW) onto SR 9; continue across the toe of the landslide. Although it's hard to see through the vegetation, the South Nooksack is meandering north just to the left (as close as 150 m as you pass the cemetery; see Fig. 9 and 10).

41.3 Watch for the junction with Rutsatz Rd - turn right. (If you cross the Nooksack bridge, you've gone too far.) This road generally follows the edge of the landslide, the top of a higher fluvial and/or ourwash terrace (lower terraces and floodplain to the left), and eventually skirts the edge of the bedrock of the north end of the Dike.

42.2 As the road makes a near-90° curve to the left, we cross from the landslide edge to a terrace, mapped as Qso2 on Raines' map (Fig. 9), and Sumas stade outwash (Qgos) by Dragovich and others (1997). Watch for the gravel pit on the right - note the well-sorted gravels.

42.6 The road rises over a low hill. This was mapped as another piece of the landslide toe by Raines, interpreted as lying on top of the terrace deposits (see Fig. 10, section B-B'); this would allow dating of the Van Zandt Dike slide as younger than that terrace deposit. However, the map of Dragovich and others (1997) does not show a protuberance of the slide deposit in this area.

43.0 The road hugs the edge of the Dike, as the floodplain of the North Nooksack occupies most of the narrow (about 1 km wide) gap between the Dike and Sumas Mountain. Watch for outcrops of Chuckanut sandstone on the right (dips NNW, 37-57°).

As the road turns from NE to east, the terrace widens - but this terrace is on the Middle Fork Nooksack lahar.

44.4 At the end of the paved road, park on the left (river side). We may look at the outcrops in the terrace scarp, or walk south oh the driveway.

Stop 5. Middle Fork lahar. We are located off the NE corner of the Van Zandt Dike, along the Middle Fork of the Nooksack. Figure 18 is an aerial view of the valley, looking up toward its source on Mount Baker. This valley is mapped as a breached anticline, between the mountains of Chuckanut rocks between the forks of the Nooksack (E) and the Van Zandt Dike and Sumas Mountain (W). Here the Middle Fork (flowing north in this reach) joins the North Fork (flowing south) (confusing enough?). Large land¬slides and volcanic debris flows have affected the drainage and topography in this area.

The Middle Fork lahar, the largest recorded from Mount Baker, was identified by Hyde and Crandell (1975, 1978), and described further by Kovanen (1996; Easterbrook and Kovanen, 1996) and Dragovich and others (1997). About 6600 yr ago, sector collapse of the Roman Wall triggered a volcanic debris flow that traveled down the Middle Fork at least as far as Cedarville (or Nugents Corner), and perhaps all the way to Bellingham Bay. It was a clay-rich (cohesive) lahar, leaving large clasts in a silty-clayey matrix, mostly of Baker andesite.

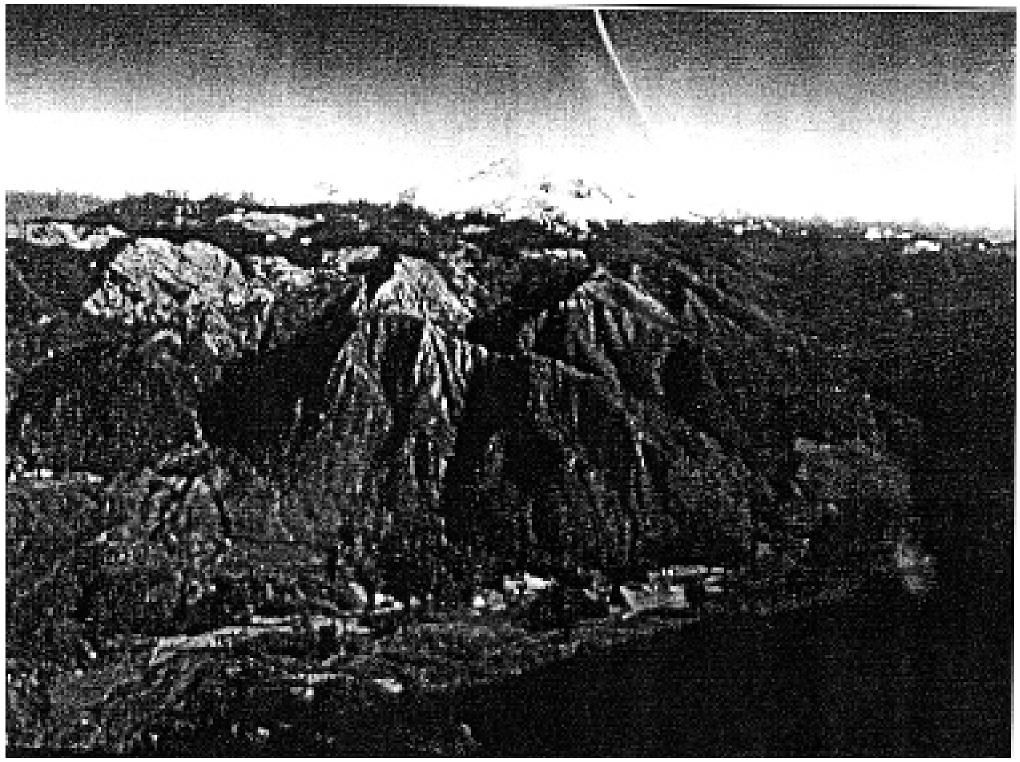

Figure 18. Oblique aerial view (to the east) of the Middle Nooksack Valley (fore-ground and right), up to source on Mount Baker. Mountains in the center underlain by Chuckanut Formation rocks (note bedding indicators); Canyon Lake Creek basin (shaded) and fan on left side. (M. J. Brunengo, 1981)

This terrace is the downstream end of the extensive lahar deposit, with variable thicknesses (3 to 25 m) of material. Perhaps the flow was constricted and ponded as it moved around the Dike; certainly much of the deposit has been removed downstream by the river. Wood (including large logs, some charred) yielded 14C ages of 6000 BP (Hyde and Crandell, 1978) and 5650± 110 BP (Kovanen, 1996). In the same eruptive episode, a hydrovolcanic eruption and second collapse caused another lahar in the Middle Fork, which spilled into the Baker River valley as well.

Figure 19, taken from Scott and others (2000), shows the extent of volcanic hazards around Mount Baker.

Along the river, there are exposures of a Chuckanut-bearing diamicton overlain by two lahars (P. Pringle, pers. pomm.). The older diamicton has a date of about 6900 BP, and may have come from a large landslide and debris flow in Canyon Creek, downstream and across the Middle Fork (the shadowed valley on the left of Fig. 18). This basin has a landslide-dammed lake ~5 km upstream. Very young radiocarbon dates (170± 100 and 160± 100 BP) from snags in the lake suggest that the latest movement may have happened in the last century, perhaps as a result of the 1872 Chelan-North Cascades earthquake, but the slide complex is probably older (Pringle and others, 1998). Note also (if the weather and sun angle cooperate) the topography of the mountains to the east, underlain by Chuckanut rocks. Porter Creek (just upstream) experienced debris torrents in 1983 and 1990; aggradation during 1990 high flows plugged the bridge and forced the creek 25 m north over the road. We might also be able to see the snags on the upper slopes, remains of the Porter Creek fire(s) of the 1930s and late 1950s.
Drive back (west) on Rutsatz Rd to the highway.

48.3 Junction with SR 9 - turn right (N), cross the bridge, and watch for a turn-off (marked "rest area") on the right.

48.5 Pull into the old bridge approach (blocked by Jersey barriers near the entrance) and park. Walk up to the edge of the low bluff along the river; at this spot, you can get a partial view of the scarp of the VZD landslide, across the river to the east.

Stop 6. Wrap-up. There are many large bedrock landslides in the western North Cascades, most dominantly in Chuckanut Formation rocks. The Van Zandt Dike landslide that we have just experienced is one of the largest. But there almost three dozen more Chuckanut mega-slides in the region (Fiksdal and Brunengo, 1980, 1981; Schmidt and Montgomery, 1995); Figure 20 shows two of them. Geologists have lavished a bit of attention on these features over the past two decades, but the specific causes (or at least, the relative importance of several causes) are yet to be determined.

In general, a landslide occurs when the forces of gravity overcome the strength of the materials on a slope. Leaving aside the possibility of sudden gravity storms, the required ingredients are a slope of some kind and some change in the relationship between stresses and strains, due to a decline in strength and/or some triggering event that serves to break the last bonds of internal friction and cohesion. There are plenty of slopes in the North Cascades, thanks to mountain uplift and erosion by water, ice, and mass wasting. The dynamic factors - strength reduction, weathering, storm or seismic triggers - are harder to unravel.
UW scientists have developed sophisticated techniques of geomorphic analysis regarding large landslides. Dan Miller (1993, 1995) generated computer models that combine

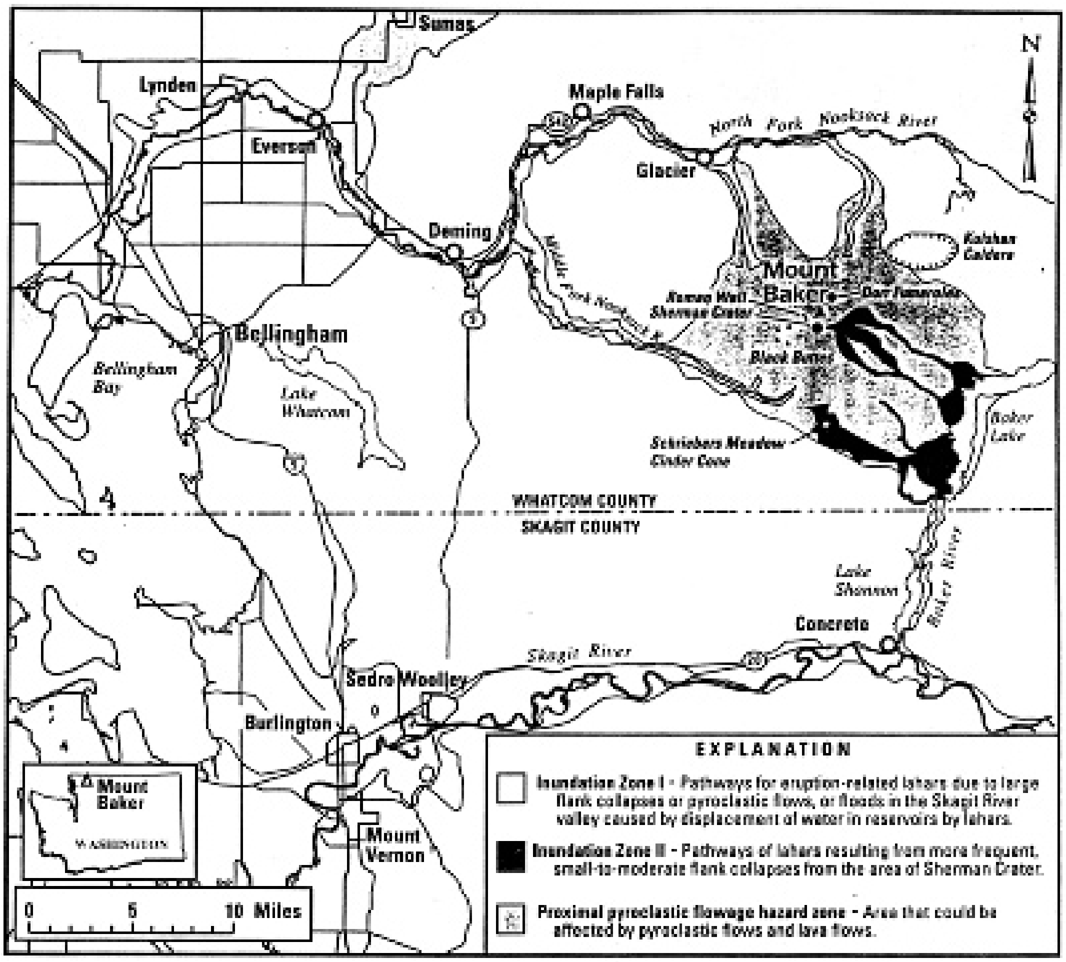

Figure 19. Geographic features and volcanic-hazard zones around Mount Baker, especially in the Nooksack and Skagit basins. (Scott and others, 2000)

stress-strength equations and GIS technology to investigate spatial variation in topography and rock properties. In relation to Chuckanut landslides, Kevin Schmidt (1994; Schmidt and Montgomery, 1995) collected topographic and rock-strength data and used them, along with physical models, to make inferences regarding the maximum topographic relief that can be sustained by various rock types. Using the mega-slides to indicate maximum relief (i.e., the landslides show that the maxima have been exceeded at those places), they found that conventional laboratory values of strength parameters overestimate the numbers back-calculated from maximum relief. In the case of the Chuckanut, the mountain-scale friction angle (cp) is about 17° for dip slopes and ~21 ° for anti-dip (scarp) slopes; corresponding cohesion values are -120 and 150 kPa, respectively. These are all well below the quantities that would be measured on intact rock samples, but similar to those obtained from1 the weakest interbed materials. Thus, rock mass strength at the mountain scale is less dependent on micro-scale material strength, and more controlled by the macro-discontinuities (joints, bedding, folds, faults). Their results indicate that topographic relief is determined by large-scale rock strength, as well as the interaction of uplift and incision.

Long-term weathering, uplift, and incision can alter the balance of stress and strength toward slope movement, but there is usually some triggering event that provides the final push to initiate it. With small debris slides, it is typically a big storm that saturates the mantle and increases pore-water pressures, reducing the effective strength of the mass; we have seen examples from the storms of 1983 and 1990. For larger landslides, increased water input due to several months or years of above-normal precipitation (or significant land-use changes) can be enough to initiate, accelerate, or reactivate a deep-seated slide. For these mega-slides, though, more serious triggers would seem to be required, if only because we don't see them popping off in every big storm or run of wet winters.

Schmidt and Montgomery (1995) also considered the role of triggers in large landslides, whether saturation (climatic) or seismic acceleration. Although they found that these reduced the threshold strengths, they did not conclude that either was responsible for the Chuckanut slides. Others have considered the role of earthquakes in triggering them. Engebretson and others (1995, 1996; also Kovanen and Easterbrook, 1996) noted the spatial coincidence of large landslides with a cluster of recorded earthquakes in this part of the North Cascades, especially the magnitude 5.2 Deming quake of 14 April 1990 and its aftershocks. The Deming quake (epicenter just north of the hill north of us) and its aftershocks were shallow, about 2.5-4 km deep, so the shaking was significant around here. Dragovich and others (1997) interpreted the seismic data to infer that the quakes occurred at or near the Chuckanut sandstone—Darrington phyllite contact, along the Macauley Creek thrust and its conjugate faults, all within about 3 km of here. They also noted the apparent correlation between seismicity and the large number of landslides in the area.

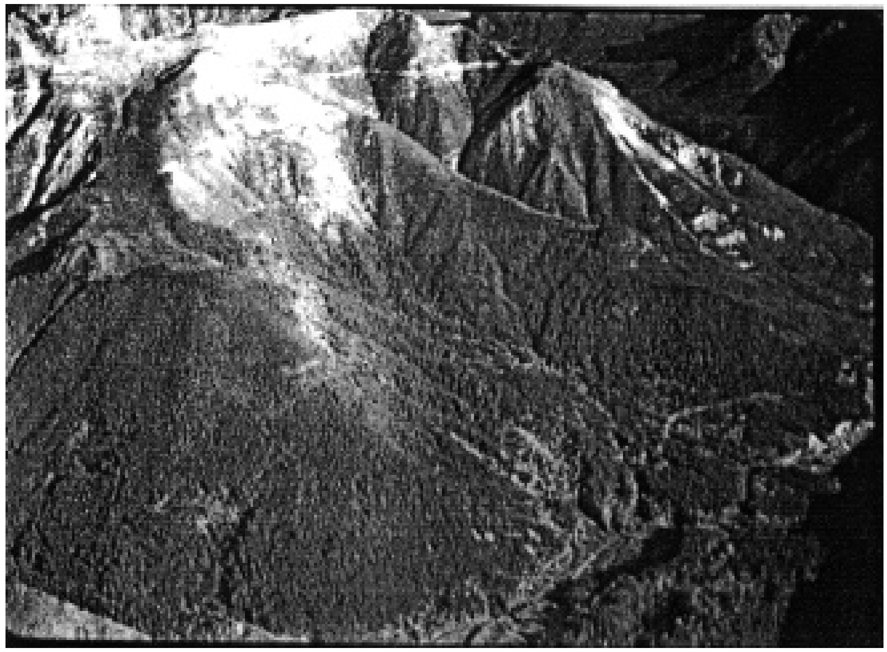

Figure 20. Aerial view of mega-slides in Chuckanut rocks: center and right (edge); Middle Nooksack at bottom right. (M. J. Brunengo, 1981)

So earthquakes may be an important trigger for large landslides in the area. It would be helpful to know the dates of major slope movements, to determine if many slides occurred in a few distinct periods. So far, there are too few dates to know for sure. Engebretson and others (1996) reported limiting radiocarbon dates from the Van Zandt landslide, of 2700 and 2400 BP from buried forests, and 1600 BP on peat on the deposit. Pringle and others (1998) interpreted calibrated 14C dates, mostly from drowned snags in landslide-dammed lakes, around several slides in the North Cascades. From the Nooksack basin, some of these were:

1) Church Mountain megaslide/sturzstrom, near Glacier: about 207 BC;

2) Canyon Lake, east of Welcome: snags have 14C ages of 160 and 170 BP, perhaps related to the 1872 North Cascades earthquake; but part of an older, undated landslide complex;

3) Racehorse Creek rock slide—debris avalanche, SE of Kendall: about 1981 BC; part reactivated in about 1950.

This record is so far too scant to draw many conclusions, especially without a good history of earthquakes with which to compare them. One inference that seems justified is that not all such mega-slides occurred during and immediately following deglaciation: some may have happened then, but several have occurred during the past few millennia of the Holocene.
Option: If there is time - walk west on the trail along the river, under the two bridges. If the water level is low, drop down to the gravel bars, and walk downstream to a point where you can see the confluence of the forks of the Nooksack. The North Fork carries more water and sediment (coarser as well?); although the North Fork is entering the South Fork's structural trough, the latter has been pushed to the west side of the valley, and is flowing along the bluffs. The Van Zandt Dike landslide probably pushed the South Fork against Stewart Mountain, perhaps damming it for a while; at least, the slide deposit seems to have influenced the gradient of the South Fork, and thus its meandering, floodplain, etc. In early historic times, logjams extended at least 3 km up the South Nooksack from here (Sedell and Luchessa, 1981), and people could cross the river on them.

This is the end of the guided trip. The junction of SR 9 with SR 542 (Mount Baker Highway) is about 0.4 mi north; turn left to go west to Bellingham.

However, taking SR 9 south will allow you to see views of the South Nooksack Valley, the Van Zandt Dike, and other features from a different perspective (or things that the hikers may not have seen at all). It takes about 30 minutes to drive to Sedro-Woolley, 45 minutes to 1-5 at Burlington, and about 80 minutes to the Mukilteo exit from 1-5.

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