GL01837

HPR - for your info then return

Department of Geology and Mineral Industries
ADMINISTRATIVE OFFICE
910 STATE OFFICE BLDG., 1400 SW 5th AVE., PORTLAND, OR 97201-5528 PHONE (503) 229-5580

VICTOR ATIYEH
GOVERNOR

September 15, 1986

MEMORANDUM

To: Interested persons
From: George Priest
Subject: Report of the CSD Review Group on the PSDC

Enclosed is part of the report of the Continental Scientific Drilling Review Group relevant to the PSDC. The report was provided for advisory purposes to the The Geosciences Research Program in the Department of Energy's Office of Basic Energy Sciences.

The steering committee for the PSDC will be implementing the Review Group's suggestion that a more focused proposal be prepared. Up to now we have only presented the overall science plan for the program. It is clearly time to move ahead to an actual proposal with a budget which is in line with the programmatic possibilities of USDOE and/or NSF. I will, however, be publishing the generalized science plan for the PSDC as an open-file report through DOGAMI this spring.

Enclosure

Lawrence Berkeley Laboratory
1 Cyclotron Road Berkeley, California 94720
(415) 486-5344 • FTS 451-5344

August 26, 1986

Dear George,

The 1986 report of the Continental Scientific Review Group is enclosed for your information. The report has been forwarded by the Lawrence Berkeley Laboratory to Dr. George Kolstad of DOE's office of Basic Energy Sciences.

With best regards,

Harold Wollenberg
Secretary, CSDRG

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

DIVISION OF EARTH SCIENCES
August 7, 1986

Dr. Thomas V. McEvilly, Head
Earth Sciences Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

Dear Dr. McEvilly:

The Continental Scientific Drilling (CSD) Review Group is pleased to forward the attached report commenting on the CSD-related activities of the Geosciences Research Program in the Department of Energy's Office of Basic Energy Sciences.

The report has been prepared by the CSD Review Group in discharge of its responsibility to render expert services to the Lawrence Berkeley Laboratory and its designees. The views expressed in the report represent a consensus of the Review Group, and you may distribute it as you deem appropriate.

The CSD Review Group held two meetings for briefing purposes at Lawrence Berkeley Laboratory on March 6 and 7 and May 1 and 2 of this year, and I wish to take this opportunity to sincerely thank you and your staff on behalf of the Review Group for the efficiency and hospitality with which LBL hosted our meetings.

Our views on the various topics discussed in the attached report developed during the course of the briefings at LBL and were crystallized during the Review Group's most recent meetings on June 11 and 13, convened during the course of the CSD Workshop held in Rapid City, South Dakota. The former was a joint meeting with the Science Advisory Committee (SAC) of DOSECC to discuss items of mutual interest in scientific drilling. Both parties considered it a productive and valuable experience, and it is likely that additional SAC-CSDRG joint meetings will be recommended in the future.

Very sincerely,

D. F. Weill

Daniel F. Weill, Chairman
(on behalf of the CSDRG)

Attachments:
CSDRG membership list
Report-1986 of the CSDRG

CSD Review Group - 1986

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REPORT - 1986

of the

CONTINENTAL SCIENTIFIC DRILLING

REVIEW GROUP

August 7, 1986

CONTENTS

Program for Scientific Drilling in the Cascades (PSDC)

At its LBL meeting of May 1-2 the Review Group heard George Priest outline the scientific rationale for an extensive CSD program in the Cascades area. The first phase of this program was further elaborated by Priest at the Rapid City workshop. It calls for an east-west geology-geophysics transect across the Cascades range as well as drilling near Santiam Pass and the Breitenbush Hot Springs area in Oregon. In the most general terms the scientific objective of the overall PSDC is " ... to develop a reliable theoretical model for processes of mass and energy transfer which occur in the volcanic mountain range above a subduction zone ..." (p. 45 of the abstracts volume from the CSD workshop at Rapid City). Without a doubt this is a significant objective, but, in the context of the CSD program, it must be distilled down to the specific drilling steps proposed to get us there.

The Review Group believes that the PSDC is now, in fact, much better defined then when it was presented at the first CSD workshop in Houston last year. Nevertheless, it needs sharper focus still. In our view the next step indicated for the Cascade consortium is to develop a proposal outlining the specific scientific goals for drilling in this area. Among the general possibilities we have heard discussed so far, we think that (1) establishing the temperature profile below the Cascade "rain curtain" effect with intermediate depth drilling, and (2) eventually identifying the (magma?) heat source below the Cascades with a deeper drilling effort are the most promising. We encourage the PSDC science team to consult with the Geosciences Program while developing such a proposal so that the proposed drilling costs are kept in phase with developing programmatic possibilities.

While we are on the subject we wish to thank Dennis Nielson for keeping us current on GTD-Industry jointly sponsored drilling in the Cascades. Thanks to his briefing during the May 1-2 LBL meeting, his talk at Rapid City and the timely EOS article of July 22 by Swanberg and Combs we and, more importantly, the geoscience community are informed about the recent results and imminent plans of the cooperative Cascade Deep Thermal Gradient Drilling Program. Although the immediate purpose of this program is to support the geothermal industry's efforts in the Cascade region, there is much obvious overlap of interest with the PSDC in particular and the CSD-thermal regimes scientific goals in general. We hope that the PSDC team will be able to put the results of this program to good use as they develop their proposal. We commend the management and scientists of this program for the prompt way in which they have announced the opportunity for further work in the holes, on core samples, and with the collected data that has been placed on open file.

PHASE I

PRELIMINARY DRILLING PLAN

PROGRAM FOR SCIENTIFIC DRILLING
IN THE CASCADES (PSDC)

Submitted to:

George Priest, Principal Investigator and Team Leader
State of Oregon
Department of Geology and Minerals Industries
1005 State Office Building
Portland, Oregon 97201

Prepared by: John C. Rowley
University of California
Los Alamos National Laboratory
Geology and Geochemistry, ESS-1
P.O. Box 1663, MS D462
Los Alamos, NM 87545

June 20, 1985

ABSTRACT

PHASE I - PRELIMINARY DRILLING PLAN - PROGRAM FOR A SCIENTIFIC PROGRAM FOR DRILLING IN THE CASCADES

One essential element of the resolution of the major scientific problems of the Cascades requires subsurface data. The approach proposed is to drill arrays of wells and coreholes across the volcanic axis of the Cascades Range. These drill holes are directed toward the basic measurements of deep thermal gradients, hydrology and *in situ* stress. This data base should aid resolutions of issues of the hydrothermal and thermal regimes of the Cascades. In addition, core, cuttings, geophysical logs, and fluid samples will provide supporting data for surface investigations and resolution of these major questions.

These preliminary drilling plans are devised to satisfy the scientific requirements in a cost-effective manner. In the choices of well re-entry, drilling, and core drilling, the nominal geologic and hydrologic conditions were factored in. The use of the existing Sunedco well and a nearby drilled hydrologic test well are evidence of the application of this approach. Core holes will yield significant geologic structure and rock property data.

These small diameter, diamond drilled holes will be lower cost, can tolerate the severe lost drilling fluid zones anticipated, and offer optimum borehole wall qualilty for *in situ* stress determinations by the hydraulic fracturing technique.

It should be realized that the drilling plans and scoping cost estimates are very preliminary. Detailed schedule, drilling programs, and improved cost estimates will be developed when the project is initiated. Detailed drilling and scientific planning will require close coordination and an intense effort to prepare drill rig specifications and requirements for each subsurface campaign. It is judged that conventional hardware and drilling equipment can be adapted and used for the proposed Phase I drilling effort. Some engineering preparation and equipment modifications will be needed. However, with sufficient time spent by knowledgable and experienced engineering personnel, these matters can be anticipated and accomodated within the procurement and contracting process. Most of the problems we anticipated to arise from potential high temperatures, up to 200°C (440°F) and by the proposed coring to a depth of 4 Km (13,000 ft). During the detailed drilling planning, development of field procedures and schedules, the project scientists with data, test equipment, and support requirements will be directly and closely involved in reviewing, revising and preparation of all drilling plans and specifications.

I. CASCADE PHASE I DRILLING AND CORING PLAN

The scientific requirements for the Phase I activities have been developed above and by Priest (1985). The resolution of the scientific issues of the structure and stratigraphy under the active Cascade volcanic arc; the heat flow, nature of the thermal source and hydrothermal systems, and the nature and properties of the pre-Cascade crust will require detailed studies of sections across the Cascade Range, roughly perpendicular to the volcanic axis. This can best be done by transects across the Cascades. The researchers involved have determined that needed subsurface data can best be obtained by a series of drill hole transects across the Cascade Range.

The first transect, the so-call Santiam Pass area, has been selected as the initial priority, i.e., the highest scientific yield option from a drilling operations standpoint. This area is characterized by a layer of younger volcanics overlaying with older volcanic rocks. It is generally anticipated that boreholes on the flanks of the pass will encounter about 300 m (1000 ft) of these younger rocks. This cover would be expected to increase to 1200 m (4000 ft) in the crest on volcanic axis locations. The younger volcanics are known to be difficult to drill, and can have zones of severe lost circulation and unstable borehole conditions.

A. Basis for the Estimates and Schedules

The following brief summary of the proposed drilling plan is based upon a preliminary, scoping analysis of the coring and drilling operations, scientific well tests, and related procedures needed to collect the desired data. Rough estimates only are presented. These were based upon past experience with similar projects. These schedule and cost estimates will be refined as the project definition, review, drilling plan scope, and scientific goals are refined.

B. Summary of Drilling/Coring Plan

Four types of drilling and coring are proposed to conduct the Phase I scientific transect across the Cascades. These consist of

(1) Testing and deeping of an existing 2.4 Km (8,000 ft) commercial (Sunedco) well to 4 Km (13,000 ft).
(2) Drill a 2-Km (6000 ft-) hydrologic test well near the Sunedco well.
(3) Diamond core-drill four, slim holes to 1.2 Km (4000 ft) depth on the flanks of Cascades in the Santiam Pass area.
(4) Drill and core a 2.7 Km (9000 ft) combined drill hole and core hole near the crest region of the Cascades; i.e, on the volcanic axis of the range.

Table I records these four major subsurface scientific efforts. A conceptual sketch of these boreholes located across the Santiam Pass is shown in Fig. 1. The individual scientific drilling projects are outlined in Table II, where the four types of drilling projects are organized within each drilling project in a sequential order of operations and procedures.

Figures 2 through 6 indicate the well bore configurations, borehole diagrams, and drilling and testing plans for the four proposed types of drilling/coring projects. Such first cut scoping type cost estimates will be refined as the PSDC scientific plan matures, and through review and refinement. Development of detailed costs of each element of the drilling/coring projects should then be performed. Finally as rig specifications and field operating plans and procedures are prepared, cost estimates will represent mature, engineering cost estimates based on evaluation of detailed local conditions, prices, and the current prices for the specific supplies, subcontractors, services, materials, and rentals needed for each drill site.

C. Preliminary Cost Scoping Estimates

Using the drilling/coring and testing plans outlined above, very preliminary cost estimates were derived. Table III is a summary of these estimates. These estimates doe not include the full suite of logs, except they do include the time to run the logs within the operationing times. Very rough estimates of the in situ stress measurements are included. They are expected to be very costly in the larger diameter holes, and much less costly in the H-size core holes.

TABLE I: SUMMARY OF PROPOSED CASCADE PHASE I DRILLING/CORING PLAN

Drilling Activity	Depth km	(ft)	Operations	Primary Tests, Research and Procedures
1. Sunedco Well				+ Geophysical logs and VSP
a. Clean out and test	2.4	(8000)	Workover rig sample and test	+ Sidewall core + Fluid sample aquifer + *In situ* stress determinations + Set protective 4 1/2 CSG string
b. Core deeper, and test	4.0	(13000)	Deep core rig; continuous core to T.D.	+ Geophysical logs + Fluid samples + *In situ* stress determinations + Set 2" protective pipe
2. Drill test well	2.0	(6000)	Air drill, small rotary rig	+ Rotary drill for hydrologic test + Core major aquifers + Geophysical logs + Hydrologic test of aquifer + *In situ* stress determination + Set 2" protective pipe
3. Core drill slim holes	1.2	(4000)	Intermediate depth core rig, H-size	+ Top to bottom core + Geophysical logs + Fluid sample + *In situ* stress determinations + Set 2" protective pipe
4. Drill/core crest hole	2.7	(9000)	Rotary to approx. 1.2 km (4000 ft); continuous core H-size to TD	+ Geophysical logs + Fluid sample + *In situ* stress determinations + Set 2" protective pipe

TABLE II

SUMMARY OF CORE/DRILLING AND TESTING

PSDC Phase I - Preliminary Sequential Operations and Procedures

I. TESTING AND DEEPING SUNEDCO 58-28

A. Outline of Workover Operations - Requires intermediate size workover rig with 3 1/2" work/drill string. (Refer to Fig. 2).

1. Relocate wellhead.
2. Clear back fill.
3. Remove cover plate and weld new casing head in place.
4. Excavate and line sump/reserve pit.
5. Mobilize workover rig.
6. Install blow-out preventor (BOP) stack.
7. Clearn out wellbore plugs (2) and heavy fluid.
8. Fish temperature probe.
9. Run geophysical logs -- full suite:

   a. gamma-gamma and spectral gamma
   b. density
   c. resistivity
   d. 4-arm caliper
   e. televiewer
   f. neutron
   g. sonic
   h. temperature
10. Conduct VSP survey.
11. Sidewall coring of major stratigraphic units (for example, twelve 15/16" by 1 3/4" cores from a single run of the Gearhart Hard Rock Coring Tool)
12. Bail or lift hole and get downhole samples of fluid from open-hole areas at about 4,027', 5,680', and 7,325'.
13. Set packer near the end of casing at about 2,600' and perforate, acidize, and bail (utilizing a cable tool rig) the cemented and cased aquifer at about 2,500' to 2,540'. Take a downhole water sample after bailing.
14. Recement the aquifer and clean hole.
15. Conduct in situ stress tests.
16. Set 4.5" casing to 8.060', cement bottom 200'.
17. Clean hole.
18. Rig down and demobilized workover rig.

B. Deep Coring Operations - Requires largest-size slim hole diamond core rig. (Refer to Fig. 3.)

1. Change out wellhead and BOP; clean sump.
2. Mobilize core rig.
3. Continuous core at H-size (3.782 x 2.500").
4. Deepen from 8,060' ± to 13,124' (k km) (temperature should be in the range of 160-250°C).
5. Run full suite of logs.
6. Bail or lift hole to clean and clear and obtain

downhole fluid samples.

7. Conduct VSP survey.
8. Conduct in situ stress tests of the lower part of the well.
9. Set 2" pipe with bottom cap; fill with waer and surround with heavy mud.
10. Rig down and demobilizing.
11. Take temperature logs during the next year. Then abandon, pulling the 2" pipe and putting cement plugs at aquifers and at 0 to 50', cut off well head, weld cover plant, backfill and restore site.

C. Current Status of Sunedco 58-Z8 Well - Detailed well data are available to project. (Refer to Figure 2.)

1. Total depth = 8,080' according to one log; 8,060' according to completion forms (drilled 10/1/81 - 12/18/81).
2. Casing record:
   0-85' = 30" diameter, 156 lbs/ft line pipe in 36" hole,
   0-288' = 20" diameter, 94 lbs/ft K55 casing in 26" hole
   0-2,622' = 13 3/8" diameter, 61 lbs/ft K55 casing in 17 1/4" hole (cut off 6' below ground level with steel plate welded on top).
3. Plugging record: 0-50' and 2,522 - 2,772'; completed 8/19/82.
4. Thermistor probe lost due to very viscous mud (8/12/82) somewhere below 5,625' - this must be fished out.
5. Available logs:
   a. daily drilling workover log
   b. NL Baroid mud log
   c. Gearhart temp. log - differential temperature
   d. Gearhart dual induction laterolog - B.H.C. sonic log
   e. Schlumberger dual induction-SFL with linear correlation log
   f. Schlumberger temp. log
   g. Detailed lithologic log by on-site geologist
   h. Thermistor temperature log by Dave Blackwell to 5,625' (stabilized temperature -- taken on 8/12/82)
   i. MRT and Pruett Kuster tool temperatures taken during and shortly after drilling

II. <u>DRILL HYDROLOGIC TEST WELL</u>

A. Location - 1.2 km (4000') deep, rotary air-mud drilled, located east of Sunedco Well 58-28 (depths developed for a possible location at T9S, R7E, Section 36.

B. Drilling Method - Air-mud rotary selected because severe lost circulation is anticipated and major purpose is hydrologic tests, and lithologic information is available from Sunedco 4.8-28 well.

C. Drilling Operations - Refer to Figure 4.

1. Prepare site with cellar ans sump.
2. Set surface conductor.
3. Mobilize rig and rig up.
4. Drill at 12 1/4" to 600-700'.
5. Set about 600-700' of 10" casing.
6. Air rotary at 7 7/8" to the aquifer (projected to be at about 4,000-5,000').
7. Core the aquifer and air lift or swab a water sample.
8. Take a downhole water sample.
9. Drill about 1,000-1,500' past the aquifer.
10. Run full suite of logs.
11. Clean hole.
12. Conduct VSP.
13. Conduct *in situ* stress determinations.
14. Set 2" pipe, capped, filled with water, and surrounded by heavy mud.
15. Rig down and demobilize rig.
16. Conduct sequential temperature logs during following year.
17. Plug and abandon after pulling pipe. Cement aquifers and put in a 50' surface plug.
18. Restore site.

III. CORE DRILL SLIM HOLES

A. Drilling Method - (Requires intermediate size diamond core rig.) Top to bottom H-size (3.782 x 2.500"). Four coreholes are required.

B. Coring Operations - Refer to Figure 5.

1. Prepare site with 4' x 6' diameter cellar with cement floor.
2. Excavate sump and prepare water supply system.
3. Mobilize rig and rig up.
4. Drill PQ (4.62") to 400-450'.
5. Team to 5" and set 4.5" casing.
6. Drill HQ to 4000'.
7. Run full suite of logs.
8. Air lift any deep aquifers and take downhole fluid samples of aquifers.
9. Run VSP survey.
10. Conduct *in situ* stress tests.
11. Set 2" pipe (water-filled, capped, and surrounded by heavy mud).
12. Rig down and demobilize rig.
13. Monitor temperatures over following year.
14. Pull pipe and abandon, cement any aquifers, and put in 50' surface plug.
15. Restore site.

IV. DRILL AND CORE DEEP HOLE

A. Location - Figure 1 illustrates the location of this combined drill and corehole. It is at or near the crest of the Cascade Range.

B. Drilling Method - The young volcanics at the top of the hole are anticipated to cause fluid loss problems, and hole stability can be expected. Air or mud rotary is selected for the top approximately 1.2 km (4,000 ft). These rocks are likely not suitable for in situ stress measurements and the thermal regime is distributed by the aquifers. Water for drilling may be a problem also.

C. Drilling Operations - Because the top section of the hole is to be rotary drilled, two alternate strategies are possible:

(a) use a small rotary rig to drill to 4,000', demobilize

(b) mobilize a large core rig to do the 5000' of continuous coring to 9000 ft.

or,

(c) select a large core rig that has rotary capability for the 4000 ft intervalto T.D.

A detailed technical (and cost) trade-off analysis is necessary to select from these two options. Therefore, only a selection sequence outline is provided for (c) above. Refer to Figure 6.

1. Establish water supply at site.
2. Prepare site with sump and cellar.
3. Mobiilze rig and rig up.
4. Set surface conductor.
5. Set 4 1/2" protective casing to 4000'.
6. Clean hole and switch over to core-drilling.
7. Diamond core H-size to 9,000; be prepared to conduct drill stem tests, air lift, or swabbing should major thermal aquifers be encountered.
8. Run full suite of logs.
9. Lift the hole and take downhole fluid samples.
10. Do in situ stress tests.
11. Run VSP surveys.
12. Set 2" pipe capped and filled with water and surrounded by heavy mud.
13. Rig down and demobilize rig.
14. Conduct sequential temperature logs for the following year.
15. Plug and abandon, pulling the pipe, cementing major aquifers, and setting a 50' surface plug.
16. Restore site.

TABLE III: PSDC PHASE I -
SUMMARY OF PRELIMINARY SCOPING OF DRILLING/CORING AND TESTING
COST ESTIMATES

Drilling/Coring Activity	Depth km	(ft)	Day/Hole	Estimated Cost[a] (K$)	Comments
1. Sunedco 58-28 A. Testing using workover rig	2.4	(8000)	90	600	Intermediate size workover rig required. Clean out and packer runs
B. Continuous coring deeper	2.4 to 4.0	(8000) to (13000)	80	1400	Largest size core rig required
2. Drill Test Well	2.0	(6000)	85	600	Medium size rotary rig required
3. Slim Core Holes	1.2	(4000)	45 each	600 each 2400 total	H-size core holes, four required. Intermediate size core rig required
4. Drill & Core Deep Crest Hole					Rig type and strategy to be determined. Coring to 3 km will require large size core rig.
A. Drill 4000'	1.2	(4000)	45	450	
B. Core to 9000'	2.7	(9000)	90	1200	
			TOTAL K$	6650	

[a] Excluding cost of geophysical logs and VSP surveys, but including hydraulic fracturing operations for *in situ* stress determinations.

SCHEMATIC SECTION OF PHASE I PSDC BOREHOLE LOCATIONS

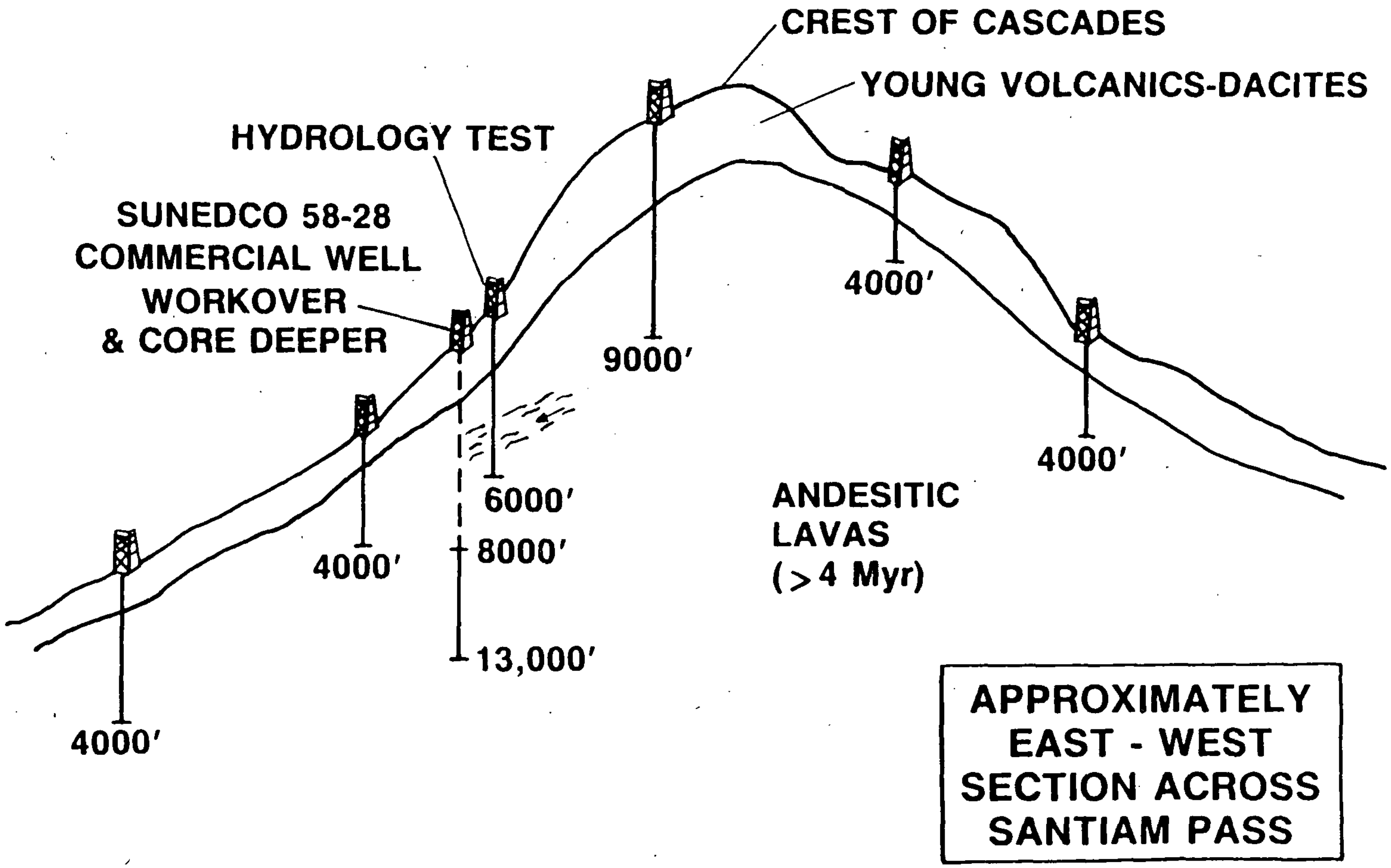
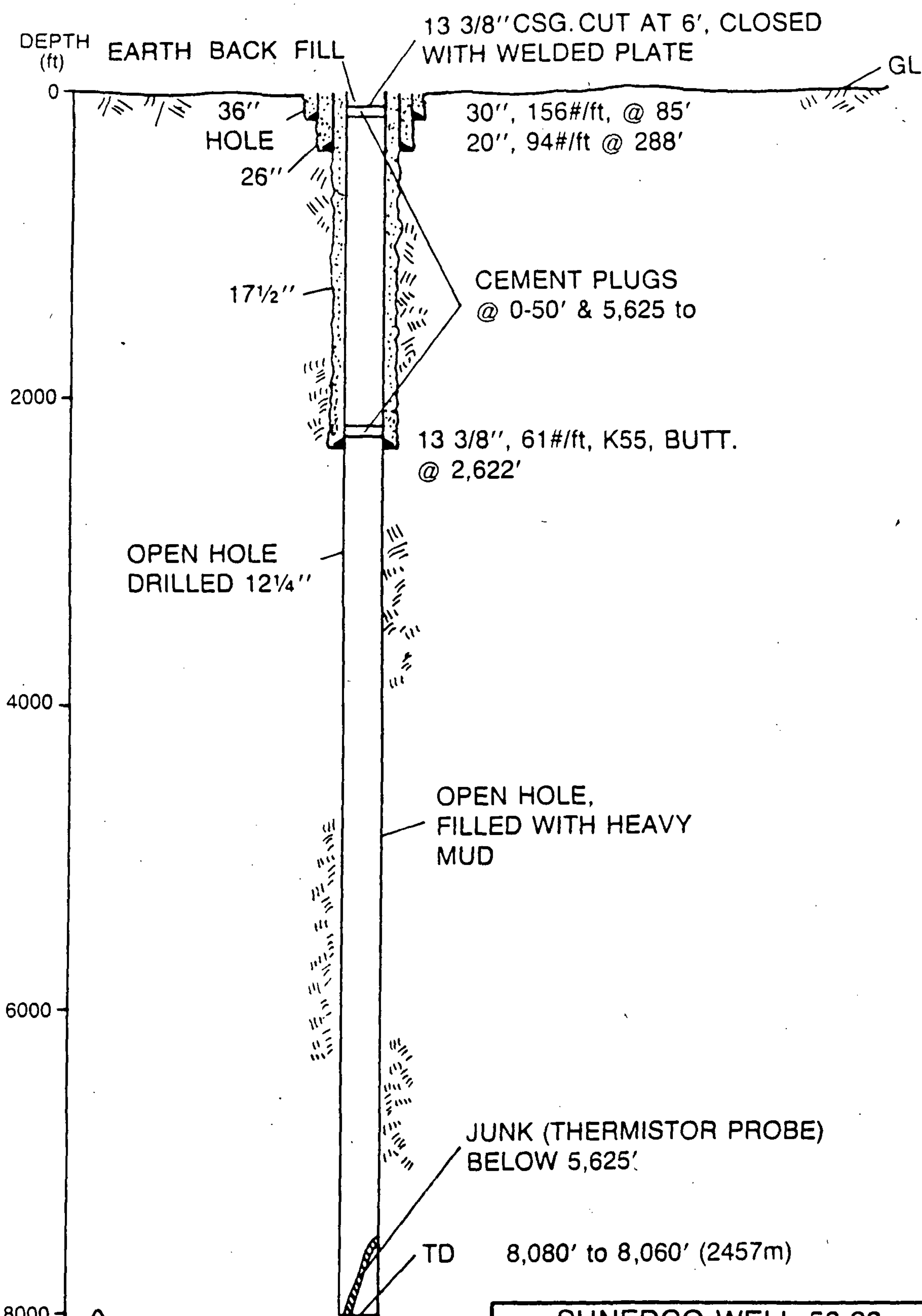
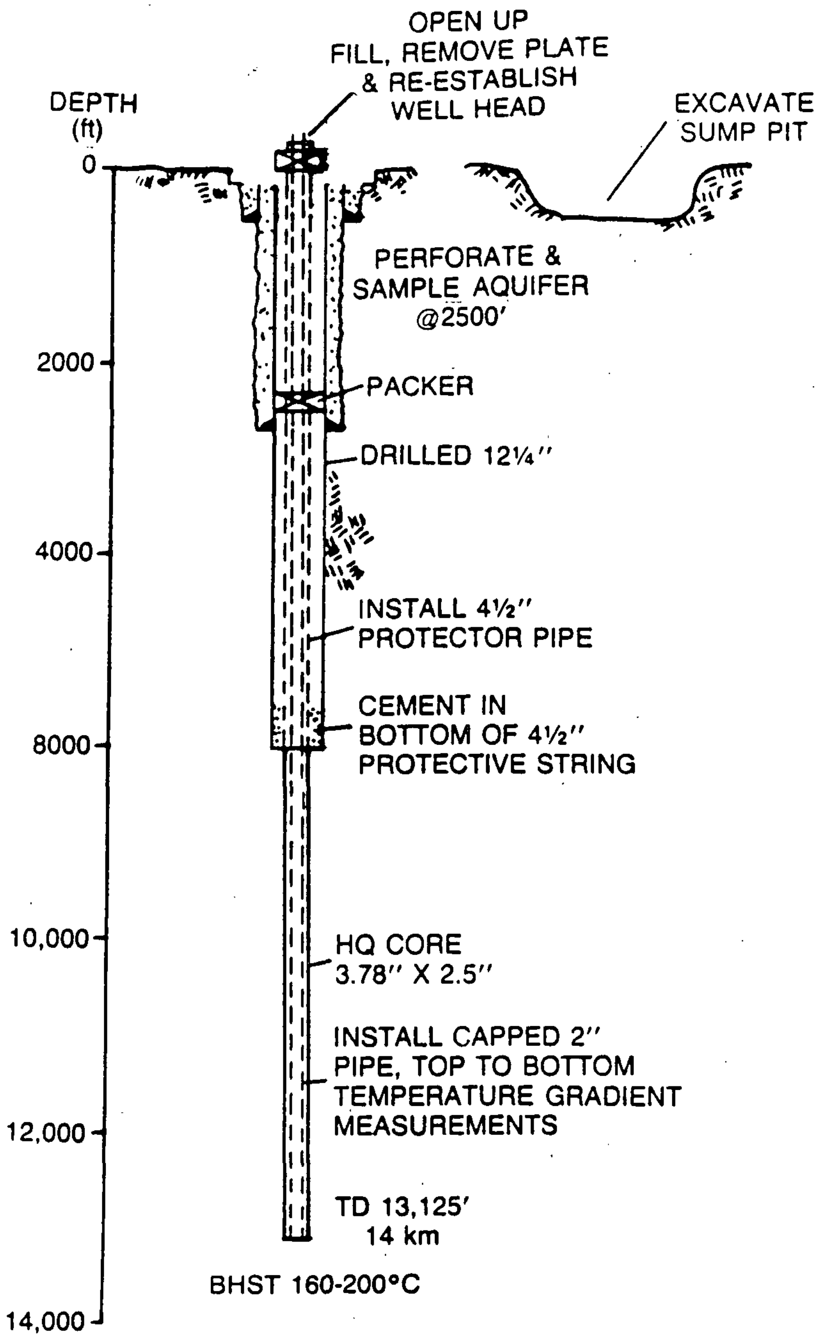


FIGURE 1



**SUNEDCO WELL 58-28
WELL BORE CONFIGURATION
AND PLUGGING CONDITION**

FIGURE 2



PROPOSED SCIENTIFIC OPERATIONS FOR SUNEDCO WELL 58-28

FIGURE 3

PHASE A-MAJOR WORKOVER OPERATIONS

1. CLEAN OUT PLUGS & HEAVY MUD
2. FISH JUNK
3. GEOPHYSICAL LOGS & SIDE WALL CORE
4. OPEN HOLE FLUID SAMPLE
5. SET PACKER AT 2,600′, PERFORATE AND ACID TREAT AQUIFER AT ±2500-2540′
6. SQUEEZE CEMENT PERFORATIONS & PULL PACKER, CLEAN HOLE
7. CONDUCT *IN SITU* STRESS TESTS
8. INSTALL 4½″ PROTECTIVE CASING AND CEMENT BOTTOM

PHASE B-DEEPEN WELL BY CORE DRILLING

1. CONTINUOUS CORE AT HQ BIT SIZE TO 4 km (13.1)
2. *IN SITU* STRESS DETERMINATIONS
3. TAKE FLUID SAMPLES
4. RUN GEOPHYSICAL LOGS
5. INSTALL 2″ PIPE & FILL ANNULUS WITH HEAVY MUD.

FIGURE 3 (continued)

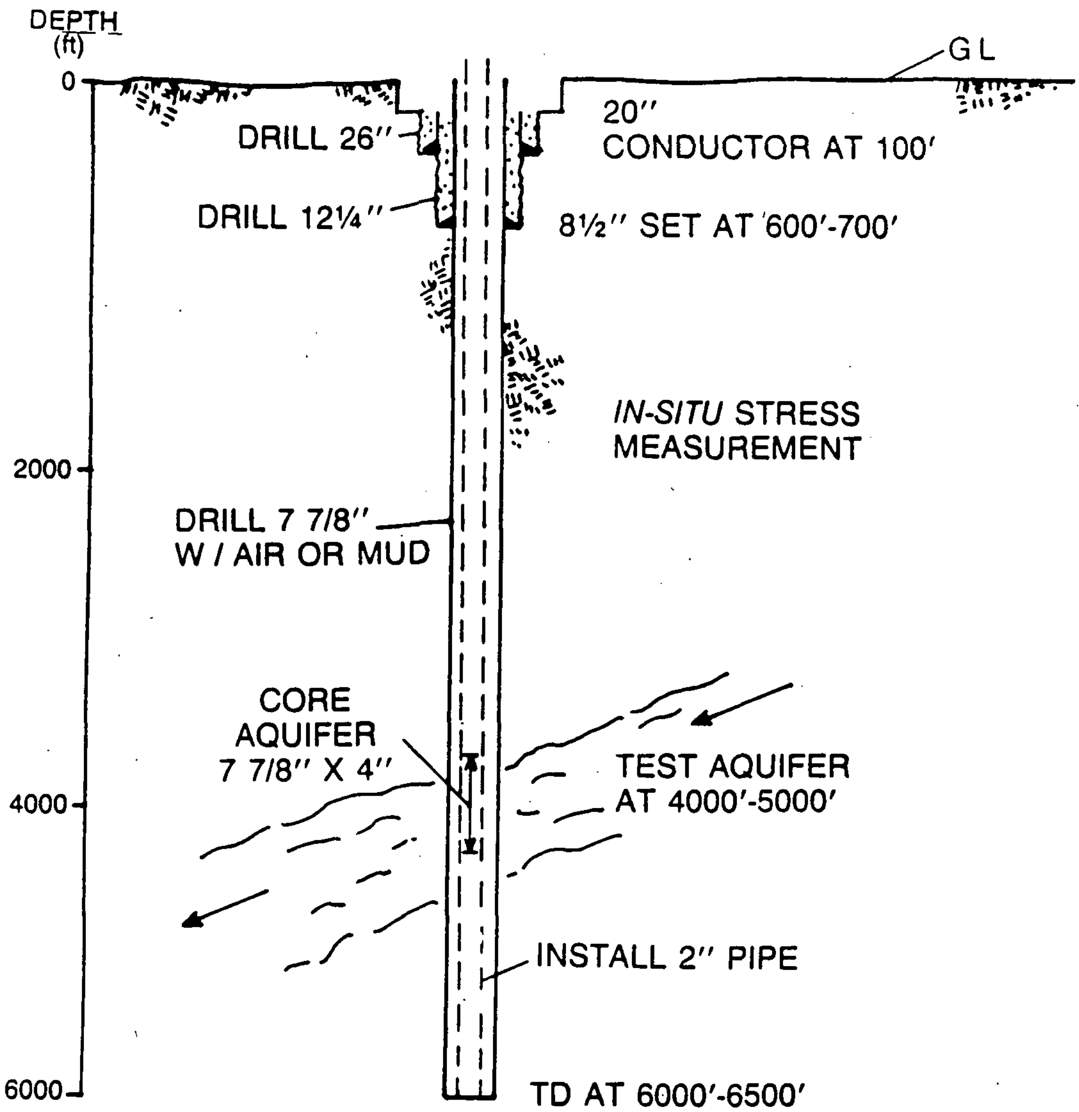
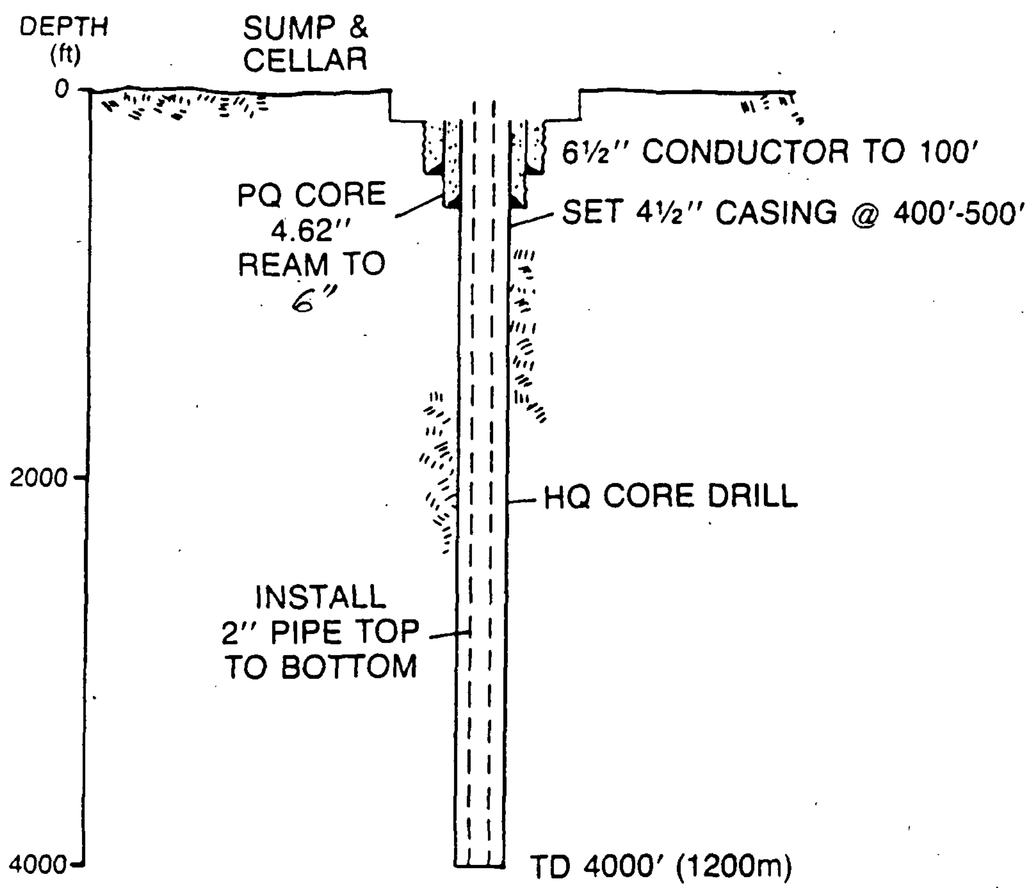


FIGURE 4

PHASE I
PROPOSED HYDROLOGIC TEST & DEEP GRADIENT HOLE. SANTIAM PASS



TESTS PROPOSED

1. GEOPHYSICAL LOGS
2. LIFT & SAMPLE DEEP AQUIFERS
3. *IN-SITU* STRESS DETERMINATION
4. LONG TERM TEMPERATURE GRADIENT MONITORING

FIGURE 5

PHASE I
PROPOSED HYDROLOGY, STRESS AND THERMAL GRADIENT HOLES; FOUR PLANNED AS TRANSECT ACROSS SANTIAM PASS

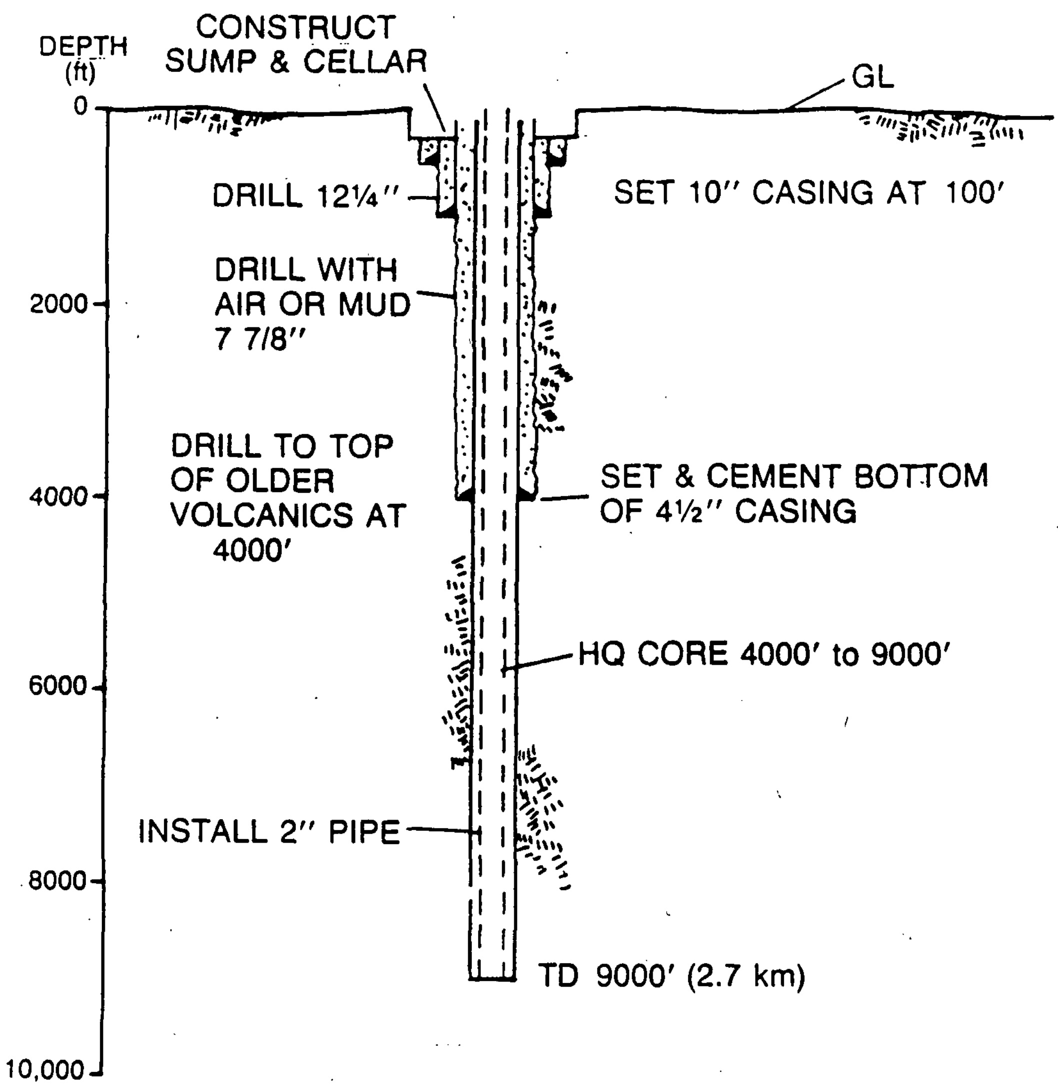


FIGURE 6

PHASE I
DEEP COREHOLE AT VOLCANIC AXIS OF CASCADES - SANTIAM PASS TRANSECT.

June 27, 1985

Mr. George R. Priest
Oregon Dept. of Geology and Minerals
1005 State Office Building
Portland, OR 97201

Dear George:

Enclosed is a brief write-up on hydrothermal mineralized systems in the Cascades. It seems to me that the disseminated systems in the Cascades porphyry belt of Washington are most analogous to the kind of thing we would like to learn about in the central High Cascades because they obviously represent large fossil hydrothermal convection systems. Thus I have emphasized these deposits. I have followed Hollister closely, as you will see from his enclosed article. I have also included a xerox copy of Don White's review article in the Seventy-Fifth Anniversary Volume of the Society of Economic Geologists in case you do not have it. This paper is a thoughtful review of the latest thinking on the relationships between mineralized systems and present-day hydrothermal systems. As White says, we have much to learn.

I hope this information is in time to assist you and that it does just that. If I can expand or modify, please let me know.

Sincerely,

P. M. Wright
Technical Vice President

PMW/jp

enclosures

MINERAL ASPECTS OF CONTINENTAL SCIENTIFIC DRILLING IN THE CASCADES

There is considerable potential that deep drilling in the Cascades will yield information of interest in terms of mineralization in this area. In the Central Cascades, all of the outcrop is geologically young in age. These young volcanic rocks presumably cover older rocks that contain mineralization which outcrop both to the south in California and to the north in Washington. Because of the obvious occurrence of heat sources in the Cascades, we presume that hydrothermal convection systems are common. Several types of ore deposits are believed to result from processes of hydrothermal convection in the continental crust. Among these types are the disseminated copper and molybdenum deposits (the so-called "porphyry" deposits), certain mercury deposits and the epithermal precious metal deposits. Lead-zinc replacement deposits typified by occurrences in the western United States and Mississippi Valley-type lead deposits are also formed by hydrothermal processes, although their relationships to known geothermal processes are poorly understood. White (1981) reviewed some presently active hydrothermal systems which are known to be precipitating metals and concluded that a variety of models of the convection and chemical processes are required to explain empirical data and that a great deal of research remains to be done in this area before we will reach an acceptable level of understanding.

In the Cascades province of California, Oregon, Washington and British Columbia there are known hydrothermal convection systems at several locations. Among these are Medicine Lake, Lassen Peak, Newberry Caldera, Crater Lake?, Mt. Hood, Mt. Ranier, Glacier Peak and Meager Creek. In addition, there is fossil evidence of hydrothermal convection in the occurrence of a number of small porphyry copper deposits (Hollister, 1978). We will briefly examine the regional setting of these deposits.

Figure 1 shows known porphyry copper occurrences along with strike-slip faults and plutons, with which these deposits appear to be closely associated. The belt of known disseminated copper occurrences extends from essentially the latitude of Yakima, WA north and into Canada. In this portion of the Cascades, Cretaceous and older sedimentary and metamorphic rocks crop out and are intruded by many granitic plutons. Presumably, a similar geologic setting, perhaps with mineralized systems, occurs in older rocks of the Oregon Cascades. Table 1 shows pertinent geologic data on these deposits.

Volcanism of the Cascade Range has been concurrent with episodes elsewhere around the Circum-Pacific region. The most effective regional tectonic force acting intermittently has been the northward movement of the Pacific plate relative to the North American plate. Movement between plates was accomodated by displacement on faults that make up the northwest-trending set on Figure 1. The spatial relationship between strike-slip faults and porphyry copper deposits suggests that the two are probably genetically related. These faults may have provided access to the surface and upper crust for material escaping from depth.

Table 1 lists the composition of the intrusion closest to ore (modified from Grant, 1969). All are calc-alkalic and quartz-bearing. In many examples, the pluton is an intrusive complex containing a dominant premineral quartz diorite phase. The smaller granodiorite and quartz monzonite phases close to mineralization are invariably younger and usually porphyritic.

All deposits have a potassic alteration zone, potassium metasomatism being ubiquitous but variable from deposit to deposit. A typical quartz-sericite-pyrite phyllic occurs within most deposits. Sulfur combining with iron in the potassic, phyllic, and argillic zones of Cascade deposits may develop pyrrhotite-rich halos rather than the typical pyritic halos more frequently seen in deposits elsewhere in the Cordilleran orogen. The frequency with which pyrrhotite porphyries are found in the Cascades sets this province apart. Both pyrite and pyrrhotite develop most strongly peripheral to the potassic zone rather than in it.

In many respects Cascade porphyry copper examples are similar to the Tertiary diapiric or stock type deposits of the Canadian Cordillera. They may be separated into Babine Lake or "inside types" containing mineralization largely within the plutonic rocks (e.g., Middle Fork) or alternatively into those deposits whose ore minerals occur mostly in a biotite-rich contact zone adjacent to a boss or stock, the Berg or "outside type" exemplified by North Fork in the Cascades. In the latter, minor mineralization may also appear within the pluton as well.

The Cascade K-Ar dates of 30, 24, 22, 18, 16, 9.9, and 6.2 m.y. shown in Table 1 agree with the geologic setting in each case. Apparent concordance between Cascade porphyry dates and Cascade volcanic rocks suggest an episodic igneous history. Volcanic episodes at 0-2, 3-7, 9-11, and 14-18 m.y. have been recognized in central Oregon Cascade volcanic rocks and examples representative of each of these episodes exist in the Cascade porphyries. In only a few cases have dates been determined for alteration silicates accompanying sulfide. The dates given are therefore largely for igneous rocks appearing to have a close time-space relationship to mineralization and mostly follow Armstrong et al. (1976).

Regarding size, Table 1 shows that the pyritic zone of most of these Cascades systems averages perhaps 5000 ft by 5000 ft and extends to unknown depth. The actual hydrothermal system can safely be assumed to be larger than this since hydrothermally altered rock typically extends well beyond the pyrite halo in most disseminated copper deposits (Lowell and Guilbert, 1970). We might determine that as much as 5 mi^3 (18 km^3) of rock would be involved in the typical Cascades belt hydrothermal convection system, assuming a vertical extent of about 2 miles, which seems reasonable. There is no a priori reason to exclude the possibility of occurrence of larger sulfide systems in the subsurface, perhaps more consistent in size with some of the porphyry copper deposits of the Southwest. For example, at Chino, New Mexico, megascopic effects of hydrothermal alteration extend 2000 to 5000 feet outward beyond the ore zone, depending on local lithology, and the system thus covers an area of roughly 5 m^2 and would perhaps encompass a volume of 10 m^3 with a 2 m vertical extent (personal information).

Regarding the coincidence of current geothermal systems and mineralized systems, it is to be noted that hot springs occur at Glacier Peak. The springs are probably unrelated to the sulfide system because of the date on the sulfide system (6 my). In addition, Mount Baker is a dormant volcano with a summit thermal-solfatara field that includes 78 000 sq m (9000 sq ft) of altered rock. Tephra associated with 1975 steam eruptions contains identifiable chalcopyrite as well as fairly common pyrite. The existence of chalcopyrite in this large currently developing alteration zone leads to speculation that a porphyry deposit is now forming within the Mount Baker thermal system.

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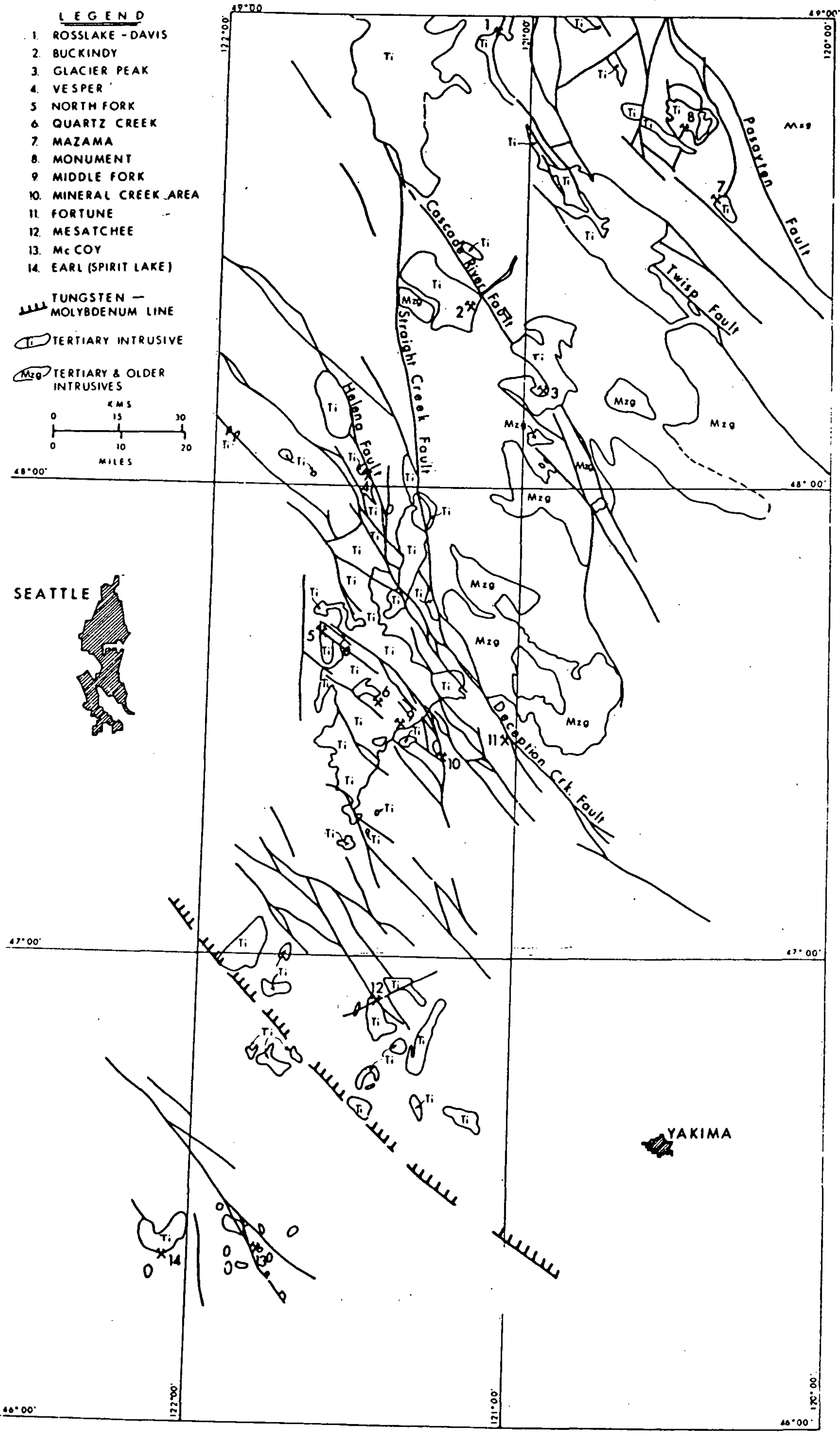


Fig. 39. Structural setting of porphyry copper deposits of the Cascades. Shear couples interpreted for Fig. 33, the compilation of structure of the northern Cordilleran orogen.

Table 14. Tertiary Porphyry Copper Occurrences of the Cascades

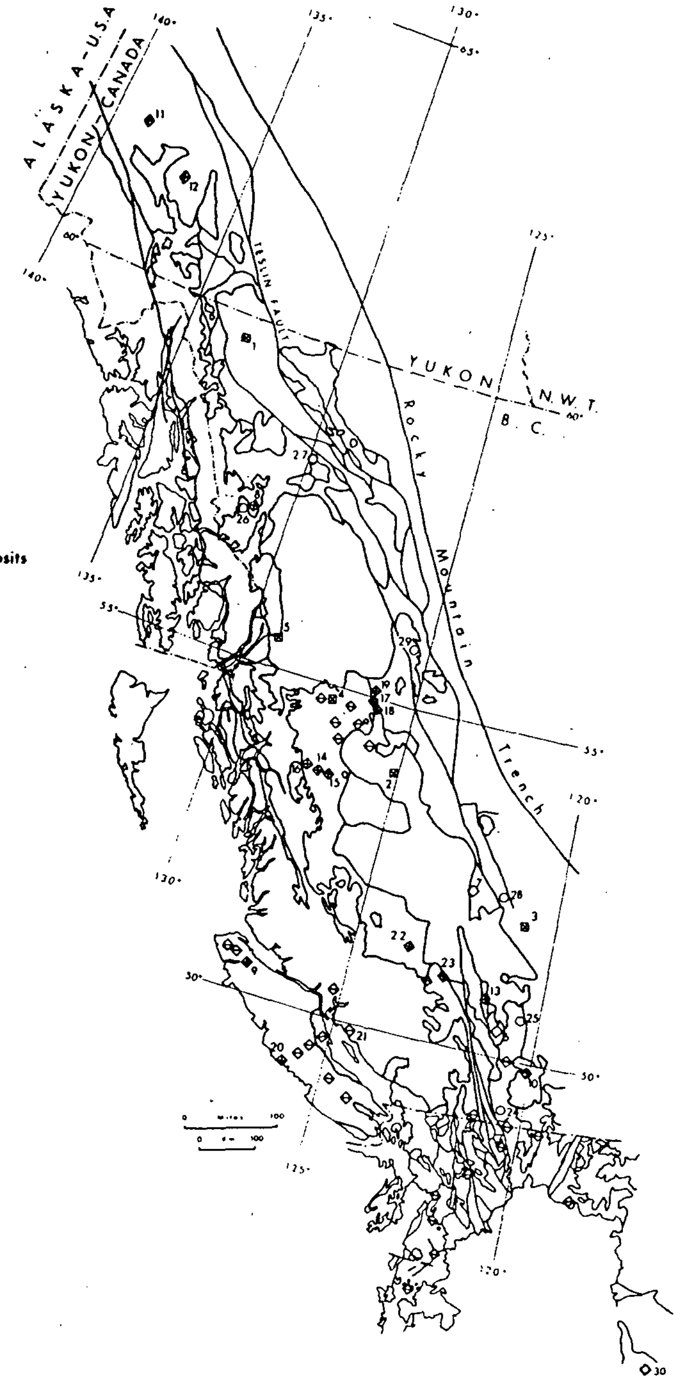
Map No.	Name in Literature	Location	Type	Pluton Age m.y.	Host Rock	Alteration Zoning Sequence from Center	Pyrite Zone: Size, m x 10^3 (10^3 x ft)	Pyrite Zone: Content in Phyllic Zone (%)	Structure Model	Major Fracture Trends	Metals Present	References
1	Ross Lake-Davis	121°08′; 48°58′	Qtz Dio Por	30	Tert Vol	Pot-Phy-Arg-Prop	1.2 x 1.2 (4 x 4)	4	Stockwork	NE-EW	Cu, Mo	Grant, 1969
2	Buckindy	121°11′; 48°22′	Grdr Por	—	Pal Gn	Pot-Phy-Arg-Prop	1.8 x 1.5 (6 x 5)	3	Stockwork	EW-NE	Cu, Mo, W	Grant, 1969
3	Glacier Peak	120°56′; 48°12′	Qtz Mon Por	22(?)	Pal Gn	Pot-Phy-Arg-Prop	2.1 x 1.5 (7 x 5)	5	Stockwork	EW-NE	Cu, Mo, W	Grant, 1969
4	Vesper	121°31′; 48°02′	Grdr Por	32	Pal Gn	Pot-Phy-Arg-Prop	1.2 x 1.2 (4 x 4)	3	Breccia	—	Cu, Mo, W	Grant, 1969
5	North Fork	121°37′; 47°37′	Qtz Dio Por	9.9	Tert Sed	Pot-Phy-Prop	—	Po	Stockwork	NW-NE	Cu	Patton, et al., 1973
6	Quartz Creek	121°29′; 47°35′	Qtz Mon Por	18	Tert Sed	Pot-Prop	1.2 x 0.9 (4 x 3)	—	Breccia	—	Cu, Mo, W	Grant, 1969
7	Mazama	120°22′; 48°36′	Qtz Dio Por	70	Cret Sed	Pot-Phy-Arg-Prop	1.5 x 1.5 (5 x 5)	3	Stockwork	—	Cu, Mo	Huntting, 1956
8	Monument	120°29′; 48°46′	Qtz Mon Por	49	Cret Sed	Pot-Phy-Arg-Prop	1.5 x 1.5 (5 x 5)	4	Stockwork	—	Cu, Mo, W	Eaton and Staatz, 1971
9	Middle Fork	121°22′; 47°29′	Qtz Mon Por	18	Tert Sed	Pot-Phy-Prop	4.6 x 1.2 (15 x 4)	4	Stockwork	NW-NE	Cu, Mo	Grant, 1969
10	Mineral Creek	121°15′; 47°25′	Grdr	Tert	Tert Sed	Pot-Phy-Prop	1.5 x 0.9 (5 x 3)	Po	Stockwork	EW-NW	Cu, Mo, W	Grant, 1969
11	Fortune	121°04′; 47°27′	Dac Por	Tert	Cret Sed	Pot-Phy-Prop	1.8 x 1.2 (6 x 4)	4	Stockwork	NW-NE	Cu, Mo, W	Gaultieri, et al., 1973
12	Mesatchee	121°24′; 47°50′	Dac Por	6.2	Tert Sed	Pot-Phy-Arg-Prop	—	Po	Stockwork	NW-NE	Cu, Mo, W	Simmons, et al., 1974
13	McCoy	121°47′; 46°22′	Qtz Dio Por	24	Tert Vol	Pot-Phy-Arg-Prop	1.2 x 1.2 (4 x 4)	Po	Stockwork	NW-NE	Cu	Huntting, 1956
14	Earl (Spirit Lake)	122°05′; 46°21′	Qtz Dio Por	16	Tert Vol	Pot-Prop (Tour)	1.8 x 1.2 (6 x 4)	—	Stockwork	NW-NE	Cu	Huntting, 1956

Tert: Tertiary
Qtz: Quartz
Dio: Diorite
Por: Porphyry

Mon: Monzonite
Cret: Cretaceous
Sed: Sediments
Gn: Gneiss

Vol: Volcanics
Dac: Dacite
Grdr: Granodiorite
Pal: Paleozoic

Pot: Potassic
Phy: Phyllic
Arg: Argillic
Prop: Propylitic
Po: Pyrrhotite



☒ Molybdenum Porphyry Deposits

1. Adanac
2. Endako
3. Boss Mountain
4. Glacier Gulch (Hudson Bay Mountain)
5. Alice Arm Area

◇ Granitic Pluton Type Porphyry Copper Deposits

6. Highland Valley Deposits
7. Gibraltar
10. Brenda
30. Cuddy Mountain

⊕ Stock type Quartz Monzonite Model Porphyry Copper Deposits

8. Liard (Shaft Creek)
9. Island Copper
11. Casino
12. Mt. Nanson
13. Maggie
14. Huckleberry
15. Ox Lake
16. Berg
17. Bell (Newman)
18. Granisle
19. Morrison
20. Catface
21. OK
22. Fish Lake
23. Poison Mountain

⊖ Other Calc - Alkalic Porphyry Cu Deposits

○ Diorite Type Porphyry Copper Deposits

24. Copper Mountain - Ingerbelle
25. Afton
26. Stikine (Galore)
27. Gnat
28. Cariboo Bell
29. Lorraine

Fig. 33. Location of major deposits. Major known porphyry deposits are located on the geologic outline used in Fig. 31. Porphyry molybdenum deposits are included for those who wish to refer to them (*compiled from various British Columbia Dept. of Mines sources*).

Table 11. Diorite Model Porphyry Copper Deposits of the Canadian Cordillera

Name	Location	Intrusion Close to Ore	Intruded	Age in m.y.	Alteration Sequence from Center	% Py in Pot Zone	Size of Py Halo	Structure
Afton	50°39′; 120°30′	Dio Sye	Trias Vol	198	Prop	1	Erratic	Stockwork
Cariboo Bell	52°30′; 121°38′	Sye Mon	Trias Vol	—	Pot-Phy-Prop	2	1.0 x 1.1 km	Stockwork
Copper Mountain	49°21′; 121°34′	Sye	Trias Vol	193	Pot-Prop	3	2.0 x 4.0 km	Stockwork
Duckling Creek (Lorraine)	55°55′; 125°26′	Sye	Trias Vol	170	Pot-Prop	1	2.0 x 3.0 km	Stockwork
Galore Creek (Stikine)	57°07′; 131°26′	Sye	Trias Vol	182	Pot-Phy-Prop	3	4.0 x 5.0 km	Breccia
Rayfield River	51°15′; 121°04′	Mon Dio	Trias Vol	—	Pot-Prop	1	2.0 x 2.6 km	Stockwork
Gnat Lake	58°11′; 129°51′	Dio	Trias Vol	—	Pot-Prop	2	1.2 x 1.5 km	Stockwork

Pot: Potassic
Phy: Phyllic
Arg: Argillic
Prop: Propylitic
Qtz: Quartz
Mon: Monzonite
Dio: Diorite
Grdr: Granodiorite
Por: Porphyry
Trias: Triassic
Vol: Volcanics
Sed: Sediments
Km: Kilometers
Sye: Syenite

Table 12. Granitic Pluton Type Porphyry Copper Deposits of the Northern Cordilleran Orogen

Name	Location	Intrusion Close to Ore	Intruded Rock	Age m.y.	Zoning Sequence from Center	% Py in Phy Zone	Size of Py Zone	Structure
Guichon Batholith (Bethlehem, Lornex, Valley)	50°29′; 121°00′	Qtz Mon Por	Trias Vol	200	Pot-Phy-Arg-Prop	3-5	Erratic	Stockwork
Brenda	49°52′; 120°01′	Grdr	Trias Vol	140(?)	Pot-Prop	1	Erratic	Stockwork
Gibraltar	52°31′; 122°16′	Qtz Diorite	Trias Vol	204	Pot-Phy-Prop	1	Erratic	Stockwork
Cuddy Mtn.	45°10′; 116°15′	Grdr Por	Trias Vol	200	Pot-Phy-Prop	2	Erratic	Bx and Stwk

Pot: Potassic
Phy: Phyllic
Arg: Argillic
Prop: Propylitic
Qtz: Quartz
Mon: Monzonite
Dio: Diorite
Grdr: Granodiorite
Por: Porphyry
Trias: Triassic
Vol: Volcanics
Sed: Sediments
Km: Kilometers
Bx: Breccia
Stwk: Stockwork

Table 13. Stock Type Porphyry Copper Deposits of the Northern Cordilleran Orogen

Name	Location	Intrusion Close to Ore	Intruded Rock	Age m.y.	Zoning Sequence from Center	% Py in Phy Zone	Size of Py Zone	Structure
Island Copper	59°36′; 127°28′	Qtz Por	Trias Vol	153	Pot-Phy-Arg-Prop	4	1.6 x 2.2 km	Stockwork
Liard (Shaft Creek)	57°19′; 130°50′	Qtz Dio Por	Trias Vol	182	Pot-Phy-Prop	3	1.0 x 2 km	Stockwork
Catface	49°15′; 125°58′	Qtz Mon Por	Pal(?) Sed	48	Pot-Phy-Arg-Prop	3	1.1 x 1.4 km	Stockwork
Granisle	54°58′; 126°19′	Qtz Mon Por	Trias Vol	51	Pot-Phy-Arg-Prop	4	1.3 x 1.3 km	Breccia
Huckleberry	53°49′; 127°10′	Qtz Mon Por	Trias Vol	80	Pot-Phy-Arg-Prop	5	1.3 x 1.3 km	Stockwork
Ox Lake	53°40′; 127°03′	Qtz Mon Por	Trias Vol	83	Pot-Phy-Prop	4	1.3 x 1.3 km	Stockwork
Bell (Newman)	55°00′; 126°14′	Qtz Dio Por	Trias Vol	52	Pot-Phy-Arg-Prop	4	1.5 x 2.1 km	Stockwork
Berg	53°47′; 127°28′	Qtz Mon Por	Trias Vol	50	Pot-Phy-Arg-Prop	4	1.5 x 1.6 km	Stockwork
Bond Creek	62°15′; 142°46′	Qtz Dio Por	Trias Vol	109	Pot-Phy-Arg-Prop	5	4.0 x 6.1 km	Breccia
Casino	62°45′; 138°48′	Qtz Por	Pal(?) Sed	70	Pot-Phy-Arg-Prop	6	3.0 x 4.1 km	Breccia
Poison Mtn.	49°21′; 120°34′	Qtz Dio Por	Cret Sed	?	Pot-Phy-Prop	1	1.0 x 1.7 km	Stockwork
Maggie	50°40′; 121°20′	Qtz Mon Por	Trias Vol	61	Pot-Phy-Arg-Prop	4	1.5 x 3.7 km	Stockwork
Fish Lake	50°46′; 133°04′	Qtz Dio Por	Trias Vol	77	Pot-Phy-Prop	2	2.5 x 3.6 km	Stockwork
Morrison	55°02′; 127°08′	Grdr Por	Trias Vol	52	Pot-Phy-Prop	3	2.3 x 2.8 km	Stockwork

Pot: Potassic	Qtz: Quartz	Por: Porphyry	Pal: Paleozoic
Phy: Phyllic	Mon: Monzonite	Trias: Triassic	Perm: Permian
Arg: Argillic	Dio: Diorite	Vol: Volcanics	Km: Kilometers
Prop: Propylitic	Grdr: Granodiorite	Sed: Sediments	Cret: Cretaceous

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GOVERNOR

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January 17, 1984

Dr. P. Michael Wright
University of Utah Earth Science
Laboratory
420 Chipeta Way, Suite 120
Salt Lake City, Utah 84108

Dear Dr. Wright:

In a recent conversation with Clay Nichols, he suggested that I coordinate an initiative for further Cascade heat flow drilling with you. As you know, our department should soon receive a modest amount of support (about $150,000) for the state-coupled geothermal program, but this is inadequate for a meaningful drilling program. Clay suggested that a separate initiative for drilling and heat flow analysis would be an appropriate action.

As you probably know, a regional heat flow study of the Western Cascades was, for the most part, completed by our group in the northern 60% of the Oregon part of the range. With the exception of Mount Hood and one hole near Mount Jefferson, no data is available from the young rocks of the High Cascade Range, owing to the masking effect of shallow groundwater. In spite of this, the western margin of the heat flow high from the High Cascade heat source has been effectively mapped in the Western Cascade Range utilizing 152 m holes. Our primary goals are: (1) to complete mapping of the remaining 40% of the western margin of the High Cascade heat flow anomaly in the southern Cascades, utilizing shallow (152 m) holes, and (2) to begin intermediate-depth (1,000 m) temperature-gradient drilling in the High Cascade Range.

We would very much appreciate your review and advice on this project, when a proposal is prepared. Your preliminary reactions to this initiative would also be appreciated.

Enclosed for your information is a summmary report of the heat flow and other data generated thus far in our Cascade research program. Because this report is the final deliverable in our current U. S. Department of Energy contract, your office should soon be receiving additional copies from the Idaho Falls office.

Sincerely,

George R. Priest

George R. Priest
Geothermal Specialist

GRP:bj
Encl.
cc: Don Hull, Clay Nichols

Ore Deposits
of the
United States, 1933-1967

THE GRATON-SALES VOLUME

John D. Ridge, *editor*

FIRST EDITION
Sponsored by The Rocky Mountain Fund

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72. Mineral Deposits of the Pacific Coastal Region

CHARLES F. PARK, JR.*

Contents

Illustrations

ABSTRACT

Mining in the Pacific Coastal Region has passed through three stages of development. First came the gold rush days, a period when gold and silver were the objects of intensive search. Second was the development of the high-grade base-metal deposits and of the smaller and more refractory precious metal deposits. And third was the modern period that covers the discovery and development of the rarer metals, of large low-grade deposits, and of the industrial and nonmetallic minerals.

Brief discussions of the salient geologic features of the region and of a few of the better known mineral deposits are given. The regional geology is favorable for continued exploration and discovery of new deposits and districts.

* Stanford University, Stanford California.

are said to have been found by the Standard Oil Company of Indiana, which has claimed large areas along the coast of Cook Inlet, Alaska. These deposits are low grade and are too high in titanium to be economic at present.

The mining industry in western Oregon and in Washington is almost inactive at present. One of the few operating mines is that at Riddle in southwestern Oregon, where the Hanna Mining Company is recovering nickel. The nickel deposits have been know since about 1864 but have been of economic value only since World War II, when they were developed as a source of supply to alleviate the shortage of nickel that resulted from the war.

GEOLOGIC SETTING

The geology of the Pacific Coastal Region is complex and highly diversified. Geomorphologically the region has narrow or absent coastal plains that rise eastward to the high and rugged mountains of the Coastal Ranges, the Cascade range, and the Chugach and other ranges in Alaska. Basin and Range topography and structure characterize parts of southeastern California and Nevada; in central California the broad well developed inland valleys of the Sacramento and San Joaquin rivers are succeeded to the east by the rugged Sierra Nevada mountains. Rocks in the region range in age from Precambrian to Recent, and most of the common sedimentary and igneous types are represented, as are also their metamorphosed equivalents. Many of the rocks are intricately folded, faulted, and metamorphosed, and near most of the mineral deposits hydrothermal alteration is extensive. The structure along the coast possibly is related to the mobile belt of deformation along the border of the continent. It is characterized by intricate and complex folding and faulting.

The sedimentary and metasedimentary rocks of California and of the extreme southwestern corner of Oregon range widely in both character and age. In southern California, the Precambrian basement is exposed in a few isolated places. Overlying this basement complex, and widely scattered throughout California, are Paleozoic limestones, sandstone, and shales, as well as their metamorphosed equivalents, and many broad exposures of Mesozoic rocks of similar types. Intruding these rocks are the extensive batholiths of the Sierra Nevada range and of southern California. Smaller, but petrographically similar batholiths and stocks crop out eastward in the desert ranges of Nevada and northward in Oregon. Probably most of these granitoid masses are of intermediate composition, tonalite, monzonite, syenite, diorite, and granodiorite, but bodies both more mafic and more silicic are present. Serpentines and altered peridotites are well exposed in the coastal ranges and along the foothills of the Sierra Nevada, and small deposits of metallurgical-grade chromite and of cinnabar are recovered from them.

The rocks in the Coastal Ranges of California, southwestern Oregon, and western Nevada, are highly faulted, folded, and in many places are metamorphosed, though the metamorphism is less intense than in parts of the inland mountains. Faulting with prominent lateral displacement, similar to the well known San Andreas fault, is widely recognized. Both extensive folding and faulting have been mapped in the metamorphosed rocks of the Sierra Nevada, and profound faulting has been described along the eastern front of the range. Eastward from the Sierra Nevada into western Nevada and also in the eastern part of southern California, typical Basin and Range structure, involving both normal and thrust faulting, is recognized.

From Mount Lassen northward through California, Oregon, and Washington, to the northern part of Washington, most of the region is blanketed with the volcanic rocks of the Cascade Mountains and the Columbia River Plateau. These rocks are mostly of Tertiary age and consist predominantly of andesitic and basaltic pyroclastics, flows, and shallow intrusive masses. They contain few mineral deposits of economic value, and they effectively mask the underlying older rocks in which are found most of the mineral deposits to the north and south. Similar flows and pyroclastic materials are irregularly distributed along the high Sierra Nevada and in patches to the east and south. Similar rocks also are widely but irregularly distributed in Alaska from the southeast through the far southwestern Aleutian Islands.

In northern Washington, the older rocks again come to the surface from beneath the volcanic materials. Here the geology resembles that of British Columbia to the north. Cretaceous and older sediments and metamorphics crop out and are intruded by many masses of granitoid rocks that are associated with the Okanogan and Coast Range batholiths, similar in composition and texture to the batholiths of the Sierra Nevada and the Nelson district of British Columbia. Igneous, metamorphic, and replacement ore deposits are commonly associated with the contact areas of these intrusive masses.

Southeastern Alaska contains extensive areas

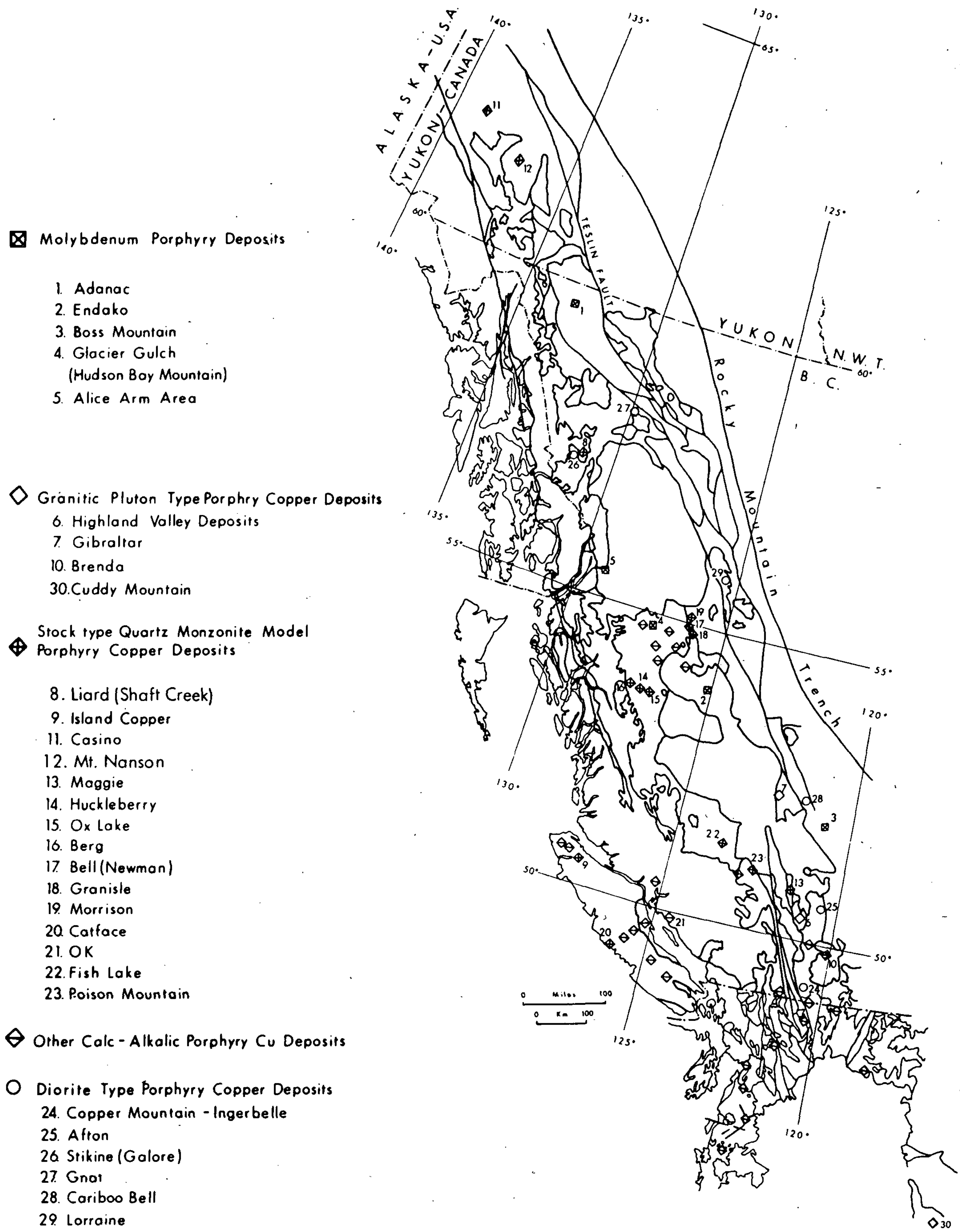

Fig. 33. Location of major deposits. Major known porphyry deposits are located on the geologic outline used in Fig. 31. Porphyry molybdenum deposits are included for those who wish to refer to them (*compiled from various British Columbia Dept. of Mines sources*).

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May 29, 1985

MEMORANDUM

To: Interested Persons
From: George Priest
Subject: USGS-sponsored Cascade Workshop, Menlo Park, California, May 22-23, 1985

The Cascade Workshop at the USGS headquarters in Menlo Park was well organized and extremely helpful to those of us interested in the Program for Scientific Drilling in the Cascades. Debates and informal discussions were encouraged by the workshop format. Issues which received the most debate were:

1. Is there any substantial amount of magma or partial melt at shallow (less than 10 km) depth anywhere in the Cascades? The seismologists found no evidence of large (>5 km) magma bodies in several study areas, but it remains unclear whether large zones characterized by small pockets of magma and small percentage partial melts could be detected by seismic surveys. The M-T data at Mount Hood is consistent with a large zone of partial melt at about 10-12 km which is much larger in areal extent than the volcano.

2. Is the Cascade heat flow anomaly caused by a zone of partial melt and very hot rock at 7-10 km or by regional fluid circulation? If the anomaly is caused by a zone of partial melt, why is there not more active volcanism in the part of the anomaly which creeps into the Western Cascades? Results from the Sunedco Well No. 58-28 near Breitenbush Hot Springs indicate that the heat flow anomaly in the Western Cascade Range persists to depths of at least 2.5 km where temperatures are probably about 160° C. If the anomaly is caused by fluids convecting heat from the High Cascades, then those fluids must be at temperatures greater than 160° C and depths greater than 2.5 km. If instead the conductive model is valid, then this might imply that the heat flow and the amount of partial melt beneath the heat flow anomaly in the Western Cascades is below some critical value necessary for production of a large active volcanic belt. This would in turn imply that conductive heat flow and partial melting beneath the High Cascades is above this critical value. Both the conductive and convective models, if true, could have a profound effect on estimates of the accessible

geothermal resource base for the Cascade Range and other subduction-related volcanic arcs.

Contributors to the PSDC met on Friday, the day after the workshop, to finalize the plan for scientific drilling in the Cascades. The basic plan submitted to DOSECC, Inc. on April 29, 1985 passed without serious modification through discussions at the main workshop and the post-workshop meeting. The first phase of the PSDC will be to study the Santiam Pass and Breitenbush areas. The second phase will expand the study to include east-west transects across the southern Washington Cascades, the Willamette Pass-Century Drive area of the central Oregon Cascades, and the Mount Shasta-Medicine Lake area of northern California. The third phase will be to drill to 7-10 km in one of the study areas. All of the drilling programs will be linked to a full suite of surface geological and geophysical surveys. Attached is the agenda for the Friday meeting with some details about the drilling program.

The following is a list of tasks which various people agreed to take on at the Friday meeting or in previous conversations. **These must be in to me by June 10, 1985**, so that I can get the scientific plan written and sent out for review by July 1, 1985.

1. David Sherrod - Gravity, aeromagnetic, and geologic section through Santiam Pass; list of hypotheses which the PSDC can test.
2. Norm Goldstein - Projected electrical cross section across Santiam Pass; 8.5" X 11" figure summarizing the electrical surveys in the Cascades; short summary of what the electrical surveys have discovered thus far; list of hypotheses which the PSDC can test.
3. Mahadeva Iyer - Projected seismic cross section across Santiam Pass; 8.5" X 11" figure summarizing the seismic data base in the Cascades; short summary of what the seismic surveys have discovered thus far; list of hypotheses which the PSDC can test.
4. Dave Blackwell - Heat flow cross section across Santiam Pass; list of hypotheses which the PSDC can test.
5. Al Waibel - Figures illustrating the evidence for the dipping aquifer in the Breitenbush area with at least one interpretive cross section showing the the various data sets superimposed; short summary of the Breitenbush geothermal-geologic model stressing relevance to studies of the Cascades as a whole; list of hypotheses which the PSDC can test.
6. Terry Keith - Theoretical cross section of the hydrothermal alteration facies through Santiam Pass, taking into account the data from the EWEB well at Santiam Junction and available data from outcrop studies in the Cascades; list of hypotheses which the PSDC can test.
7. Mike Wright - Brief summary of how the PSDC can test the hypothesis that the High Cascade volcanic arc is

underlain by plutons which are generating porphyry copper-type alteration and mineralization. What is the evidence from the Western Cascade plutonic rocks and contemporaneous British Columbia plutons which bears on this issue? What are the implications of the porphyry copper model for geothermal exploration (i.e. what is the depth and lateral extent of 200° C+ fluids in a typical porphyry system)?

8. Dick Couch - Figures showing the gravity and aeromagnetic data base in Washington, Oregon, and northern California; figure showing a calculated gravity section through the Santiam Pass area and, if possible, a detailed section through the Breitenbush area (the Breitenbush section should be at the 1:62,500 scale); short summary of the results of gravity and aeromagnetic work done thus far; list of hypotheses which the PSDC can test.
9. Bob Mariner - Cross section showing the possible hydrologic models for the Santiam Pass and Breitenbush areas; short summary of what has been learned about the Cascade hydrologic model thus far; list of hypotheses which the PSDC can test.

Those contributors who have access to a drafting department should send in the figures in final form if possible. This will greatly aid our overloaded drafting staff and will help get the scientific plan out on time. Detailed cross sections through the Santiam Pass or Breitenbush areas should be at the 1:62,500 scale.

The scientific plan for the PSDC will be published through the Oregon Department of Geology and Mineral Industries in October or November of 1985. This plan will not be a proposal but will serve as the framework for proposals and will include an appendix with some generalized cost estimates .

May 24, 1985
Menlo Park, California

PROGRAM FOR SCIENTIFIC DRILLING IN THE CASCADES

MEETING AGENDA

Summary of results of the April 29, 1985 DOSECC meeting in Houston - Dave Blackwell

Summary of **informal** proposal submitted on short notice to DOSECC - George Priest

Phase I - Three-year study of Breitenbush-Santiam Pass

1. Gravity, electrical, and seismic surveys
2. Map two 15' quadrangles
3. Deepen Sunedco Well No. 58-28 to 4 km
4. Drill a 2 km well east of Well No. 58-28
5. Drill four 1.2 km (4,000') slim diamond core holes across Santiam Pass
6. Drill a 2.7 km (9,000 ') well - Santiam Pass area
7. Estimated cost = 9.7 million dollars (total on p. 12 of the DOSECC proposal is in error)

Phase II - Two-year study of three additional transects

1. Areas = Mt. Shasta-Medicine Lake; Willamette Pass-Century Drive; southern Washington Cascades
2. No detailed description of work elements given
3. Lesser cost per transect relative to Phase I budget stressed with following specific points:
   a. Surface surveys of Mt. Shasta-Medicine Lake are already done or in progress
   b. Modest drilling program consisting of 400 m temperature gradient holes for S. Wash.
   c. Drilling at Willamette Pass-Century Drive and at Mt. Shasta-Medicine Lake will consist of four 1.2 km slim holes and deepening one hole to 2.0 km in each area.
4. Estimated cost of Phase II = 10 million dollars

Phase III - Deep hole

1. Drill to 7-10 km in one of the four transects
2. Special drilling and logging technologies needed
3. Drilling could take several years
4. Estimated cost = 50-100 million dollars

Discussion of final scientific plan for the PSDC

Assignment of specific responsibilities for contributors

STATE OF OREGON 1859
VICTOR ATIYEH
GOVERNOR

Department of Geology and Mineral Industries
ADMINISTRATIVE OFFICE
1069 STATE OFFICE BLDG., PORTLAND, OREGON 97201 PHONE (503) 229-5580

June 26, 1985

MEMORANDUM

To: Interested Persons
From: George Priest
Subject: Location of proposed PSDC drill site SE of Breitenbush Hot Springs

The location of the proposed PSDC well east of the Sunedco Well 58-28 was listed in the handout at the USGS Cascade Workshop. For those of you that did not get the handout, the proposed site is located in Section 36, T9S, R7E on USFS road 4685.

This well will be aimed at intercepting the same aquifer hit in Well 58-28 at a greater depth and higher temperature. The goal will be to examine changes in the fluid and alteration as water ascends from High Cascade heat sources. There is good evidence from geologic mapping that the Oligocene to early Miocene sequence strikes northeast and dips about 6-10^{o} southeast in this area. If the aquifer is controlled by a fractured welded tuff unit, then the proposed well should cross the aquifer between about 4000' and 5,500'.

For those of you who attended the Menlo Park meeting, Al Waibel misread his notes when he commented that the aquifer is in a dipping sill. His lithologic log for Well 58-28 indicates that the aquifer is in welded tuffs with evidence of shearing.

STATE OF OREGON 1859
VICTOR ATIYEH
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October 17, 1984

TO: Cascade Task Force and Interested Persons

FROM: George Priest

SUBJECT: Presentation of the Program for Scientific Drilling in the Cascades (PSDC) at the 1984 AGU meeting, San Francisco

The PSDC proposal will be summarized at the annual AGU meeting in a series of 15-minute talks during a half-day session on Thursday, December 6, 1984 in Room 327 of the Civic Auditorium between 8:30 A.M. and noon. The session will be followed at 7:00 P.M. by an informal meeting for contributors and interested USDOE and NSF officials to discuss funding strategies. The location of the evening meeting will be announced later.

For those actively contributing to the proposal, please come prepared to give a 15-minute oral presentation. A slide projector and a projector for 8½"-11" transparencies will be provided. The following is a tentative schedule for the talks:

8:30- 8:45	Introduction and major objectives by George Priest
8:45- 9:00	Heat flow studies by David Blackwell
9:00- 9:15	Drilling program by John Rowley
9:15- 9:30	Rock mechanics experiments by Bezalel Haimson
9:30- 9:45	Well logging by Richard Traeger
9:45-10:00	Hydrothermal studies by Edward Sammel, Robert Mariner, and Terry Keith
10:00-10:15	Coffee Break
10:15-10:30	Seismic studies by Mahadeva Iyer, Walter Mooney, Douglas Stauber and Craig Weaver
10:30-10:45	Gravity studies by Richard Couch
10:45-11:00	Electrical geophysical surveys by Harve Waff and Norman Goldstein
11:00-11:15	Geologic studies by George Priest, Edward Taylor, and Gary Smith
11:15-12:00	Questions and discussion

It would be advisable for those of us presenting material to have a coordination meeting prior to the Thursday presentation. I will arrange for a place to meet on Wednesday evening.

In the interim, I would like to thank those of you who have sent in your parts of the revised proposal. Please try to send in separate budget and task descriptions for the new Phase I (one transect) and the new Phase II (one transect each in Washington, Oregon, and California). Some of you have not split up these budgets or have not discussed Phase II work in Washington and northern California. I think it would be appropriate to develop very similar areal data for each of the four transects. Please make sure that the areal surveys, particularly the geophysical work, address all four transects, even if only to discuss why a new survey is not needed in a particular area.

I have not received any objections to choosing the Santiam Pass area for Phase I, so those of you still writing sections of the proposal can assume that Phase I will occur at Santiam Pass. For those doing experiments in the drill holes this will mean that Phase I will involve sampling and testing the Sunedco Breitenbush Well, as well as the two 4,000' wells and the 6,800' crest well. The Breitenbush Well is probably about 9,000' deep, although we won't know the actual depth until the confidentiality periods ends in December, 1985. If Sunedco grants permission, which is likely, we will want to reenter this cemented well and conduct tests, so budget for this eventuality. I will be talking with Sunedco representatives about this in the next few weeks.

GRP:ab

4

Porphyry Copper Deposits of the Northern Cordilleran Orogen

CONTENTS

INTRODUCTION

This chapter summarizes characteristics of porphyry copper deposits within the Cordilleran orogen east of the Coast Range plutonic complex of the Yukon and British Columbia and south to the Columbia River plateau and the Idaho batholith. Porphyry copper deposits in this area reflect a geologic environment different from that found for mineralized intrusions elsewhere in the Cordilleran orogen, both to the south in the United States and Mexico and to the west in Alaska. A section on the Tertiary Cascade porphyry copper province is included herein. The Cascade province is considered separately because its deposits display a unique mineralogy and age of mineralization. That portion of the Cordilleran orogen described in this chapter is shown in Fig. 32, with the Cascades shown in Fig. 39 (see p. 114).

The regional geology of this area has been described by Monger, et al. (1972), Hollister (1974), Wolfhard and Ney (1974), Field, et al. (1974), and Stacey (1974). Each offer slightly differing views on the post-Mississippian evolution of the geology in this porphyry copper province. The descriptive geology in this chapter has benefited from many discussions with J. E. Armstrong and J. W. H. Monger.

Two separate petrologic models have been used popularly to categorize porphyry copper deposits in this area, a diorite and a quartz monzonite model. The diorite model, which involves a mineralized quartz-free pluton, has also been called the alkalic type (*CIM Special Volume* 15, 1976, and Soregaroli, 1975) and the syenite suite (Sutherland Brown, et al., 1971). The quartz monzonite model has also been named the calc-alkalic type (*CIM Special Volume* 15, 1976) and includes mineralized quartz-bearing plutons compositionally ranging from quartz diorite to granite, with the igneous phase closest to ore in time and space commonly being quartz monzonite.

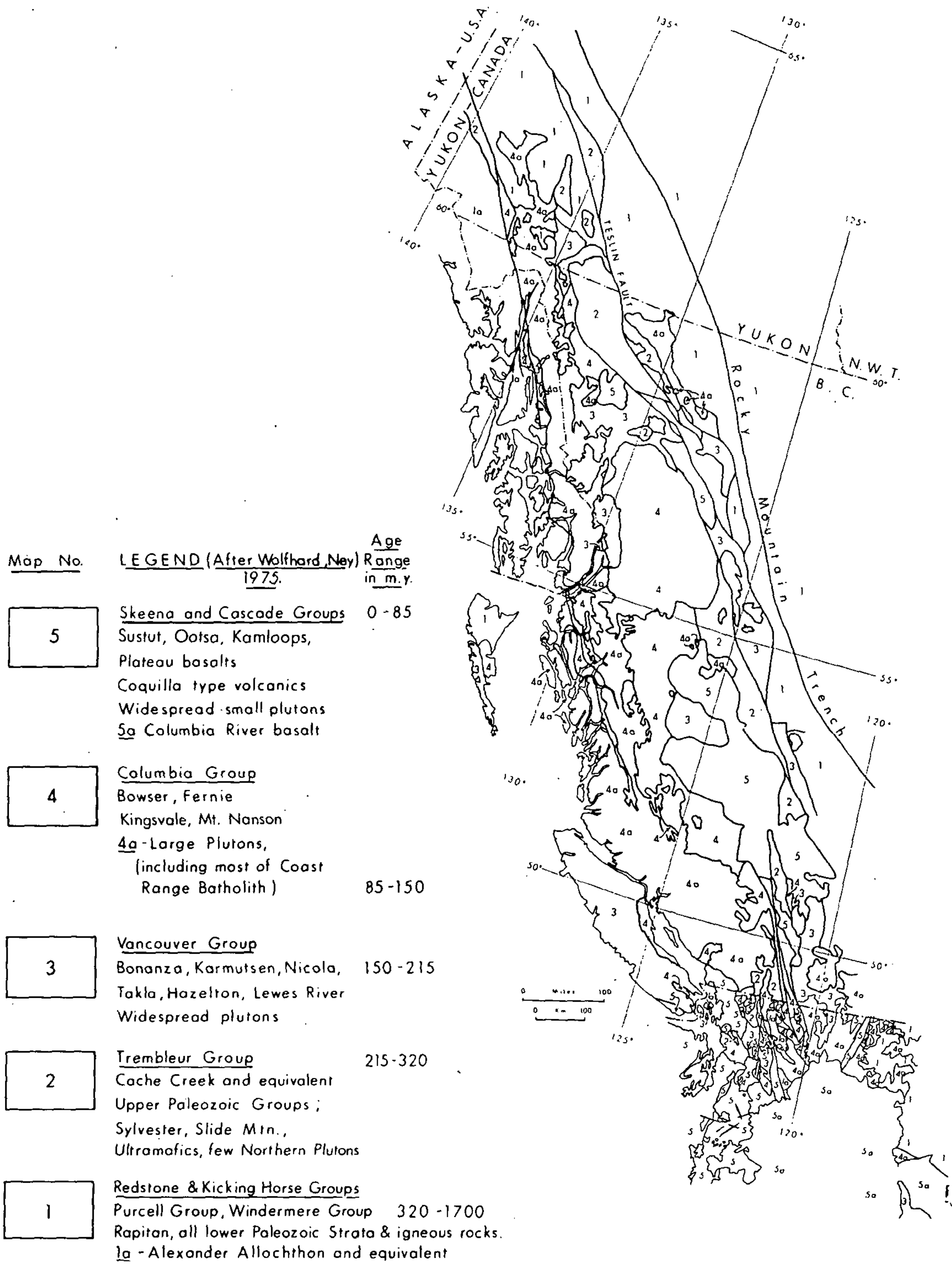


Fig. 32. Geologic index map, northern Cordilleran orogen. Geologic map showing metallogenic epochs of Wolfhard and Ney (1975). These metallogenic epochs coincide with stratigraphic-tectonic units and are used in that sense in the text. Porphyry copper deposits have been dated from the youngest three map units used in this summary (*modified from Wolfhard and Ney, 1974*).

The quartz monzonite model has been further divided into granitic pluton type (Field, et al., 1974) and stock type (including the volcanic and phallic types of Sutherland Brown, 1972). The stock type contains porphyry deposits associated with small plutons or dikes. Some consideration is given in this chapter to modifying the Lowell and Guilbert (1970) model so that quartz monzonite model deposits of this area can be described by it.

Table 11 summarizes data on the largest known diorite-type deposits within the area. Table 12 is a compilation of data on the most important known granitic pluton-type deposits, and Table 13 lists the most important stock types. Deposits listed in these tables are shown in Fig. 33. Molybdenum porphyries (Clark, 1972) are omitted from consideration in this chapter as are large copper-bearing skarn deposits.

GEOLOGIC SETTING

Late Paleozoic and Mesozoic geologic development of the Canadian Cordillera (Fig. 32) is unusual for the eastern Pacific rim. Because geologic evolution from Mississippian time on was particularly influential in the development of deposits in this porphyry copper province, the post-Mississippian geology of this portion of the Cordilleran orogen is discussed in some detail. The geology in this chapter largely follows Wolfhard and Ney (1974) and *CIM Special Volume* 15 (1976) and is basically the same as that found in White (1959) and Monger (1975).

Wolfhard and Ney (1974) propose and name a number of metallogenic epochs. These epochs also have been used as stratigraphic-tectonic elements and are used in that fashion in this chapter. The map units in Fig. 32 correspond to these metallogenic epochs.

Map Unit One: Map unit one includes all the cratonic, platform, and shelf deposits and any associated igneous rock that predate 360 m.y. in the area of this map unit. These stratigraphic-tectonic elements are generalized and equated to the Redstone and Kicking Horse metallogenic epochs by Wolfhard and Ney (1974). They comprise the cratonic sialic crust that was rifted, dextrally faulted, folded, and intruded in ensuing time. Porphyry copper deposits formed as one consequence of successive younger tectonic events. The Alexander terrane of Berg, et al. (1972) is set aside as a unit in Fig. 32, as are the Lower Paleozoic and Precambrian rocks of the Cascades.

Map Unit Two: Map unit two is the Trembleur metallogenic epoch of Wolfhard and Ney (1974) and consists of the stratigraphic-tectonic element formed in the 360 to 215 m.y. period. It includes Cache Creek and equivalent groups (e.g., Sylvester and Slide Mountain) that occur in the area of this map unit. As described by Wheeler, et al. (1972), Cache Creek includes all the elements of oceanic crust. The tectonic significance of oceanic crust between the Alexander terrane and the Cascade Paleozoics on the west and the North American craton on the east is not entirely clear, but seems to imply western tectonic transport for rocks represented by map unit 1a, Alexander terrane, which has been identified west of the oceanic crust. Carbonatites near the western margin of the cratonic block of Mississippian(?) age may be speculated to be coeval with earliest development of oceanic crust and to coincide with early distensional tectonics.

Map Unit Three: Map unit three (Fig. 32) is the tectonic-stratigraphic element that includes dominantly marine volcanic assemblages with dates from 215 to 150 m.y. It is called the Vancouver metallogenic epoch by Wolfhard and Ney (1974) and includes Nicola, Takla, and Hazelton groups on the mainland and Bonanza and Karmutsen formations on Vancouver Island. The Triassic and pre-Upper Jurassic Bonanza and Karmutsen calc-alkalic, marine volcanic, and sedimentary rocks on Vancouver Island are similar in some respects to the stratigraphically equivalent Nicola-Hazelton-Takla groups. These latter, however, include alkalic members that developed in a distensional environment whereas volcanic formations on Vancouver Island do not have alkalic flows and

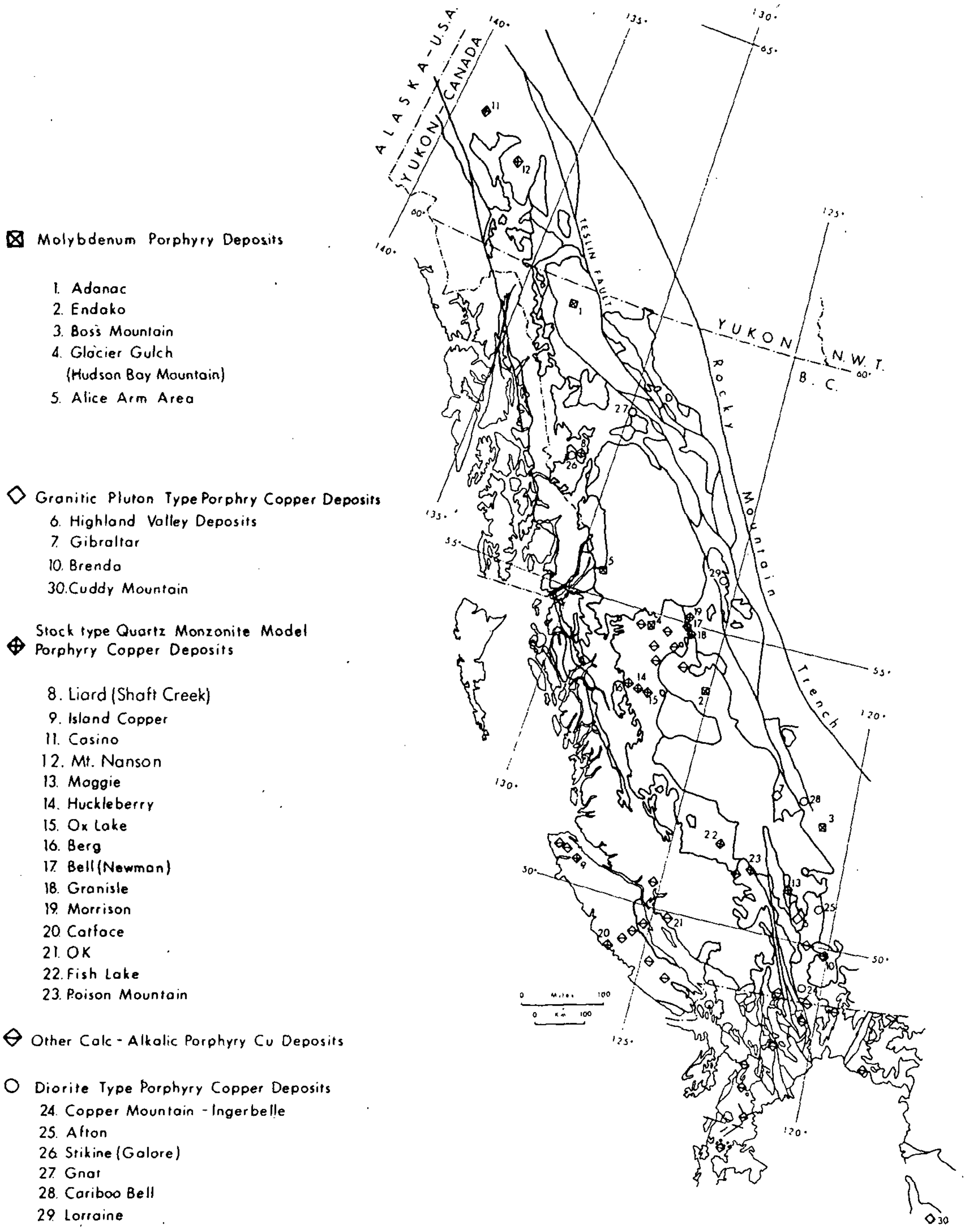


Fig. 33. Location of major deposits. Major known porphyry deposits are located on the geologic outline used in Fig. 31. Porphyry molybdenum deposits are included for those who wish to refer to them (*compiled from various British Columbia Dept. of Mines sources*).

Table 11. Diorite Model Porphyry Copper Deposits of the Canadian Cordillera

Name	Location	Intrusion Close to Ore	Intruded	Age in m.y.	Alteration Sequence from Center	% Py in Pot Zone	Size of Py Halo	Structure
Afton	50°39′; 120°30′	Dio Sye	Trias Vol	198	Prop	1	Erratic	Stockwork
Cariboo Bell	52°30′; 121°38′	Sye Mon	Trias Vol	—	Pot-Phy-Prop	2	1.0 x 1.1 km	Stockwork
Copper Mountain	49°21′; 121°34′	Sye	Trias Vol	193	Pot-Prop	3	2.0 x 4.0 km	Stockwork
Duckling Creek (Lorraine)	55°55′; 125°26′	Sye	Trias Vol	170	Pot-Prop	1	2.0 x 3.0 km	Stockwork
Galore Creek (Stikine)	57°07′; 131°26′	Sye	Trias Vol	182	Pot-Phy-Prop	3	4.0 x 5.0 km	Breccia
Rayfield River	51°15′; 121°04′	Mon Dio	Trias Vol	—	Pot-Prop	1	2.0 x 2.6 km	Stockwork
Gnat Lake	58°11′; 129°51′	Dio	Trias Vol	—	Pot-Prop	2	1.2 x 1.5 km	Stockwork

Pot: Potassic
Phy: Phyllic
Arg: Argillic
Prop: Propylitic

Qtz: Quartz
Mon: Monzonite
Dio: Diorite
Grdr: Granodiorite

Por: Porphyry
Trias: Triassic
Vol: Volcanics
Sed: Sediments

Km: Kilometers
Sye: Syenite

Table 12. Granitic Pluton Type Porphyry Copper Deposits of the Northern Cordilleran Orogen

Name	Location	Intrusion Close to Ore	Intruded Rock	Age m.y.	Zoning Sequence from Center	% Py in Phy Zone	Size of Py Zone	Structure
Guichon Batholith (Bethlehem, Lornex, Valley)	50°29′; 121°00′	Qtz Mon Por	Trias Vol	200	Pot-Phy-Arg-Prop	3-5	Erratic	Stockwork
Brenda	49°52′; 120°01′	Grdr	Trias Vol	140(?)	Pot-Prop	1	Erratic	Stockwork
Gibraltar	52°31′; 122°16′	Qtz Diorite	Trias Vol	204	Pot-Phy-Prop	1	Erratic	Stockwork
Cuddy Mtn.	45°10′; 116°15′	Grdr Por	Trias Vol	200	Pot-Phy-Prop	2	Erratic	Bx and Stwk

Pot: Potassic
Phy: Phyllic
Arg: Argillic
Prop: Propylitic

Qtz: Quartz
Mon: Monzonite
Dio: Diorite
Grdr: Granodiorite

Por: Porphyry
Trias: Triassic
Vol: Volcanics
Sed: Sediments

Km: Kilometers
Bx: Breccia
Stwk: Stockwork

Table 13. Stock Type Porphyry Copper Deposits of the Northern Cordilleran Orogen

Name	Location	Intrusion Close to Ore	Intruded Rock	Age m.y.	Zoning Sequence from Center	% Py in Phy Zone	Size of Py Zone	Structure
Island Copper	59°36′; 127°28′	Qtz Por	Trias Vol	153—	Pot-Phy-Arg-Prop	4	1.6 x 2.2 km	Stockwork
Liard (Shaft Creek)	57°19′; 130°50′	Qtz Dio Por	Trias Vol	182	Pot-Phy-Prop	3	1.0 x 2 km	Stockwork
Catface	49°15′; 125°58′	Qtz Mon Por	Pal(?)Sed	48	Pot-Phy-Arg-Prop	3	1.1 x 1.4 km	Stockwork
Granisle	54°58′; 126°19′	Qtz Mon Por	Trias Vol	51	Pot-Phy-Arg-Prop	4	1.3 x 1.3 km	Breccia
Huckleberry	53°49′; 127°10′	Qtz Mon Por	Trias Vol	80	Pot-Phy-Arg-Prop	5	1.3 x 1.3 km	Stockwork
Ox Lake	53°40′; 127°03′	Qtz Mon Por	Trias Vol	83	Pot-Phy-Prop	4	1.3 x 1.3 km	Stockwork
Bell (Newman)	55°00′; 126°14′	Qtz Dio Por	Trias Vol	52	Pot-Phy-Arg-Prop	4	1.5 x 2.1 km	Stockwork
Berg	53°47′; 127°28′	Qtz Mon Por	Trias Vol	50	Pot-Phy-Arg-Prop	4	1.5 x 1.6 km	Stockwork
Bond Creek	62°15′; 142°46′	Qtz Dio Por	Trias Vol	109	Pot-Phy-Arg-Prop	5	4.0 x 6.1 km	Breccia
Casino	62°45′; 138°48′	Qtz Por	Pal(?)Sed	70	Pot-Phy-Arg-Prop	6	3.0 x 4.1 km	Breccia
Poison Mtn.	49°21′; 120°34′	Qtz Dio Por	Cret Sed	?	Pot-Phy-Prop	1	1.0 x 1.7 km	Stockwork
Maggie	50°40′; 121°20′	Qtz Mon Por	Trias Vol	61	Pot-Phy-Arg-Prop	4	1.5 x 3.7 km	Stockwork
Fish Lake	50°46′; 133°04′	Qtz Dio Por	Trias Vol	77	Pot-Phy-Prop	2	2.5 x 3.6 km	Stockwork
Morrison	55°02′; 127°08′	Grdr Por	Trias Vol	52	Pot-Phy-Prop	3	2.3 x 2.8 km	Stockwork

Pot: Potassic
Phy: Phyllic
Arg: Argillic
Prop: Propylitic

Qtz: Quartz
Mon: Monzonite
Dio: Diorite
Grdr: Granodiorite

Por: Porphyry
Trias: Triassic
Vol: Volcanics
Sed: Sediments

Pal: Paleozoic
Perm: Permian
Km: Kilometers
Cret: Cretaceous

have not been assigned such a setting (Stacey, 1974).

Nicola, Takla, and Hazelton rocks of map unit three occur east of the Alexander terrane (or allochthon), both west and east of the Cache Creek ophiolite (map unit two), and west of the North American craton. Their base is only rarely exposed, but Preto (1975) reports Triassic and Lower Jurassic fossils occur in Nicola volcanogenic sediments associated with marine tholeiites, feldspathoid-bearing alkalic and subalkalic tholeiites, and volcanic differentiation products (e.g., dacite). These volcanic rocks include coeval calc-alkalic, alkalic, and subalkalic units.

The Triassic and Lower Jurassic volcanic rocks, regardless of setting, are the best host for most porphyry copper deposits in the Canadian Cordillera irrespective of age and are thus an important factor in prospecting for and positioning of these deposits.

Intrusions through and comagmatic with the Triassic Nicola-Takla-Hazelton or equivalent volcanic assemblages east of the Alexander allochthon do not appear to be typical products of an arc-trench environment. Sierra Nevada type batholiths are missing, as is Franciscan type trench melange. Groups of alkalic and dioritic plutons occur comagmatic with undersaturated volcanics in remarkably linear zones over many miles (Fox, 1975). Normal faults active over a considerable period of time have not only controlled the position of the dioritic and alkalic intrusive centers but the distribution of associated alkalic volcanic rocks as well.

On the other hand, Triassic and Lower Jurassic calc-alkalic plutons comagmatic with extrusives of the Nicola and Takla groups are typically zoned with a basic outer shell giving way gradationally inwards to a more alkalic and silicic core. These zoned plutons extend from Texas Creek in Alaska to Cuddy Mountain in Idaho (Field, et al., 1974). The large zoned calc-alkalic plutons that have copper associated with their core phases are the granitic pluton type porphyry copper of Field, et al. (1974). The diorite type porphyry copper is the alkalic, commonly zoned, diorite-monzonite-syenite pluton where copper occurs in or near the younger differentiates. Therefore, porphyry copper deposits may have a quartz-bearing quartz monzonite (calc-alkalic) or quartz-free diorite (including alkalic) host.

Why two distinct suites of plutons (alkalic and calc-alkalic) occur in the same general area, each originating simultaneously with the same set of volcanics but presumably from a different crustal depth although in response to the same tectonic regime, is not clear. The alkalic volcanic rocks and plutons form an unusual setting for porphyry copper deposits in that they seem to satisfy the criteria for a spreading center, and the zoned mineralized plutons comagmatic with them are probably the roots or magma chambers of old alkalic volcanic centers.

Unmineralized batholithic calc-alkalic plutons with dates that range from 185 to 165 m.y. have been found in the Yukon east of the Shakwak fault. Middle Jurassic batholithic plutons have also been dated in the southern Cordillera near the 49th parallel.

The Columbian orogeny (Wheeler, et al., 1972) apparently closed this period of mixed alkalic and calc-alkalic volcanism and plutonism.

Map Unit Four: Map unit four (Fig. 32) includes various rocks that comprise the stratigraphic-tectonic unit formed in the interval 150 to 80 m.y. It is called the Columbia metallogenic epoch by Wolfhard and Ney (1974) and included with this stratigraphic tectonic element are the Bowser, Fernie, Kingsvale, and Mount Nanson groups as well as most of the Coast Range plutonic complex. The Granvina-Nutzotin arc-trench accumulations in Alaska as well as back arc type basin accumulations of this age east of the batholiths infer that the plutonic complex is the axis of an island-arc volcanic belt.

Larson and Pitman (1972) have found a long period of normal magnetic polarity to extend from 110 to 80 m.y. Wanless (1969) reports numerous radiometric ages for batholiths in the Canadian Cordillera from this period. Wanless (1969) also reports common dates from the coastal batholith in the 50-42 m.y. interval, although in terms of volume of batholithic material formed the 110-80 m.y. interval is the most important.

Larson and Pitman (1972) interpret the magnetic quiet intervals as periods of rapid sea-floor spreading. Subduction during these intervals was therefore more rapid and batholithic plutonism increased. Concurrent with the increase in subduction rates, compressional tectonics were dominant. Major folding and thrusting on the continents but not major transcurrent faulting have been stratigraphically dated to coincide with the magnetic quiet zones of the oceanic basins (Wheeler, et al., 1972).

As noted on Tables 11, 12, and 13, very few dated porphyry copper deposits have ages occurring within this period of batholithic activity. Because porphyry copper deposits uniformly exhibit extensional structural conditions, the compressive tectonic environment accompanying more rapid subduction and corresponding to periods of more pronounced batholithic activity should not be favorable to their formation. Dating on deposits in the Canadian Cordillera confirms this negative correlation.

Map Unit Five: Map unit five, the Skeena and Cascade metallogenic epochs of Wolfhard and Ney (1974), represents the stratigraphic-tectonic element formed from 80 m.y. to the present. A significant break at about 42 m.y. separates the older stock and small batholith-dominant igneous activity from the plateau bimodal volcanism more common in the younger Cascade metallogenic epoch. These epochs include the Sustut, Ootsa, and Kamloops groups and Coquihalla type volcanics. A large number of K-Ar dates within the range 50-42 m.y. are now available for batholithic plutons in the Coast Range plutonic complex. These have made some other K-Ar dates younger and confused somewhat the distribution of plutons by age.

Most porphyry copper deposits dated in this epoch are diapric. They occur in areas where regional stress was characterized and dominated by strike-slip faulting (Monger, et al., 1972). The host for the Tertiary porphyry copper deposits appears to have been largely Triassic volcanic rocks (Fig. 35). Tertiary porphyry copper deposits mostly penetrated the Lower Mesozoic volcanic terrane, which included the older comagmatic diorite and granitic pluton type porphyry deposits. The reappearance in the Tertiary of porphyry copper deposits in the Triassic volcanic terrane is unusual in the eastern Pacific rim.

Porphyry copper deposits do not commonly occur outside the Lower Mesozoic volcanic rocks whereas porphyry molybdenum type occurrences are known within the Coast Range plutonic complex and with some larger plutons (Sutherland Brown, et al., 1971). The absence of porphyry copper deposits combined with the presence of porphyry molybdenum deposits in the Coast Range plutonic complex could be ascribed to a difference in type of crust. This speculation is not yet supported by adequate geochemical or geophysical data.

Structure

Fig. 34 compiles strike-slip faults mapped by the Geological Survey of Canada, the US Geological Survey, the British Columbia Dept. of Mines, and the Washington State Dept. of Natural Resources within the area of this chapter. It is modified after Seraphim and Hollister (1975). Thrust faults are generalized or omitted in the vicinity of the 49th parallel, the Alaska-Canada border, and the eastern part of this section (e.g., Rocky Mountain thrust belt) because porphyry deposits are only rarely associated with this type of fracture.

The fracture pattern shown in Fig. 34 is compatible with that which would develop if a Pacific plate moved north with respect to the North Amercian plate. The major shears trend about N35W (e.g., Pinchi, Teslin, and Tetlin faults) and the major tensional fractures trend nearly north-south. Together these form the Pacific plate-North American plate stress diagram (Fig. 34). The structural elements conjugate to these two fracture directions could also include shears trending about N35E. The northeast set is locally identifiable

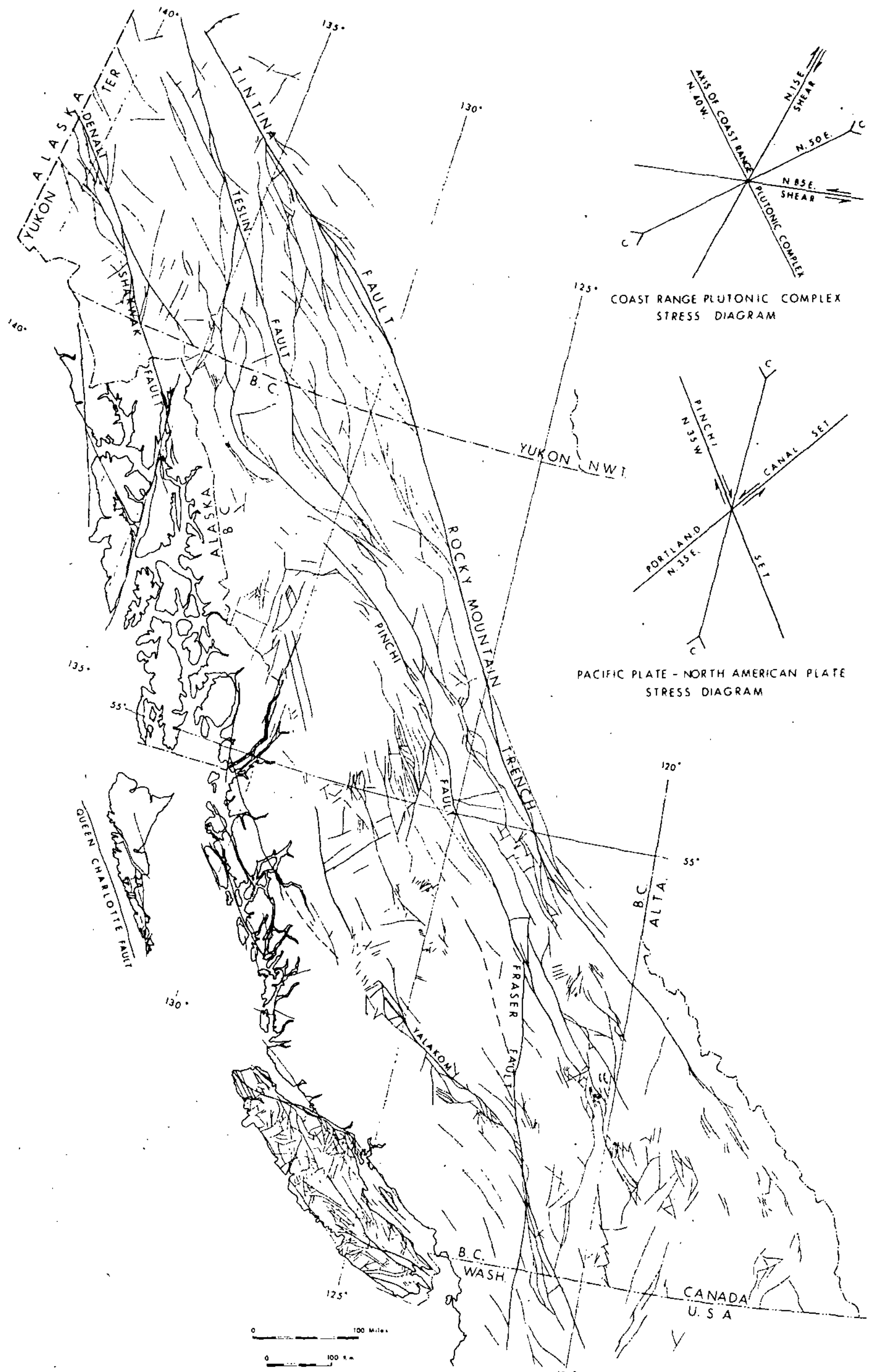


Fig. 34. Structure in the northern Cordilleran orogen. Major strike-slip faults known to exist in the northern Cordilleran orogen are shown on this map. Most porphyry deposits shown in Fig. 32 fall near a major strike-slip fault. Thrust faults, fold axes, and plutonic rocks have been omitted to simplify the map (*compiled from various British Columbia Dept. of Mines and Geological Survey of Canada sources and from Seraphim and Hollister, 1975*).

although not as well developed as the Pinchi. The north-south tensional fractures formed (as in the case of the Highland Valley) simultaneously with the N35W compressive shears having right lateral movement and therefore are related to the causative force of the strike-slip tectonics.

The northwest shears form a branching inter-fingered network of transcurrent faults whose west blocks invariably have moved north. Fault displacements are generally younger on the westernmost shears. The amount of movement on these displacements has not been determined either separately or as a whole. On the other hand, movement of the Pacific plate relative to the North American craton could be hundreds of kilometers. Aggregate movement on all northwest shears between Vancouver Island and the North American craton also may have been hundreds of kilometers. It is clear from this reasoning that anything west of the Rocky Mountain trench may be allochthonous with respect to rocks east of the trench and the numerous branching northwest—trending right lateral faults in reality may form one large fault zone separating the craton from the Pacific plate. Most porphyry deposits occur close to one of the major strike-slip faults and the spatial association of the two suggest a genetic connection. It would be logical to assume that these faults provided access to the upper crust for the porphyry magma.

Thrust faults in this area generally are compatible with a separate and distinct N50E compressive force. The tension fractures and strike-slip faults associated with N50E foreshortening make up the Coast Range plutonic complex stress diagram (Seraphim and Hollister, 1975) in Fig. 34. Because the Coast Range plutonic complex and the fold axes in its vicinity trend N40W, it would seem that the compressive force that resulted in the thrusts was genetically related to Coast Range plutonism and folding. Subduction during parts of the Jurassic and Cretaceous appears responsible for the northeast-trending compressive force (Monger, et al., 1972) as well as the N40W fold axes and intrusion-related manifestations of northeast compression. Vertical shears related to this compressive force that trend approximately N85E (with the north block moving west) and N15E are identifiable within the Cordilleran orogen, but these lack the continuity, number, or significance of the N35W set of the Pacific plate-North American plate stress diagram.

Porphyry copper deposits appear timed to occur most frequently during periods of strike-slip tectonics rather than during periods of northeast compression (Hollister, 1974). Since few deposits actually occur directly on strike-slip faults, however, the faults characterize the tectonic style within which the porphyry copper deposit is most likely to develop.

The N50E-oriented compressive force would appear to be episodic and dates on batholithic plutons within the Coast Range plutonic complex may be related to peak periods of compression. If this conjecture is accepted then the compressive force oriented N50E may have been most active in the periods 165 to 160, 110 to 80, and 50 to 42 m.y.

The compressive force oriented north-south may also have been episodic. The oceanic crust of map unit two (Cache Creek) could be considered a product of both rifting and strike-slip faulting related to northerly movement of the Pacific plate relative to the North American. Should this be more conclusively demonstrated eventually, the north-south compression may have operated as far back as the interval from Mississippian to mid-Triassic. If dating on the porphyry copper deposits developed on strike-slip faults may be used to date fault displacements, it is possible that porphyry dates could be used to infer timing of the north-south force. If this speculation is accepted, the north-south force could have been active in the periods 215 to 170, 153 to 140, and 83 to 65 m.y. Based on stratigraphic evidence, it appears to have been effective through most of Early Tertiary.

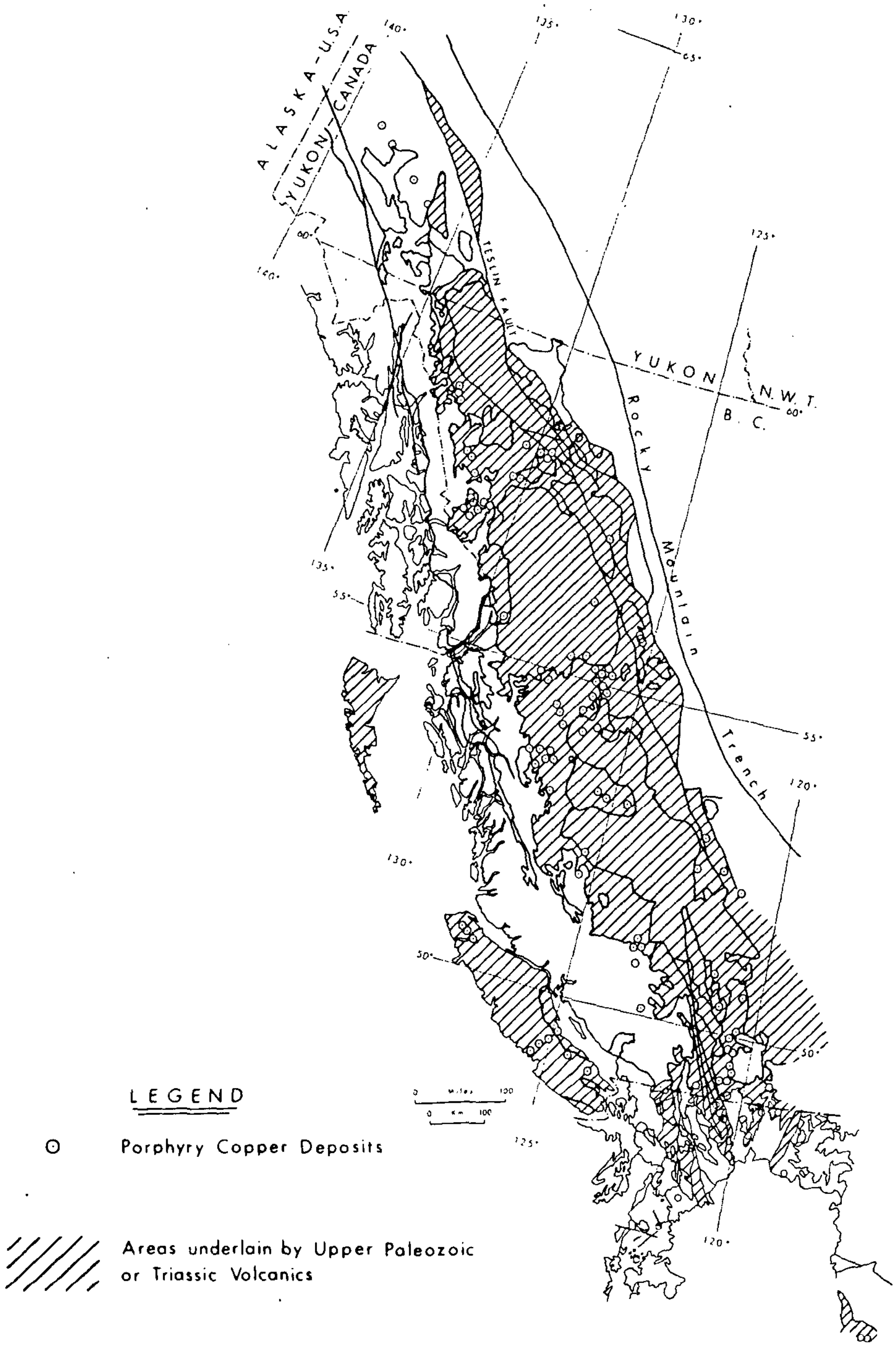


Fig. 35. Distribution of porphyry copper deposits. Porphyry copper occurrences in the northern Cordilleran orogen regardless of economic potential are shown on this map together with those areas of the subsurface that include with their sialic crust Permian or Triassic basic marine volcanics. Relatively few occurrences are known outside the areas where basic marine volcanics are suspected in the crust (*modified from Hollister, 1974*).

Discussion

The appearance of Triassic-Lower Jurassic diorite and granitic pluton type and Tertiary quartz monzonite stock type porphyry copper deposits in the same terrane justifies a more detailed examination of crustal setting.

A step-by-step growth in recognition of the Alaskan Paleozoic or Alexander allochthon was enhanced with the discovery of an anomaly in Permian fossils by Ross (1967). This anomaly was further developed by Monger and Ross (1971) and Jones, et al. (1972). Their investigations have led to recognition that pre-Mississippian rocks west of the outcropping Permian-Triassic-Lower Jurassic sedimentary and volcanic rocks—i.e., west of the stratigraphically complex and extensive Cache Creek-Hazelton-Takla-Nicola groups—are allochthonous with respect to the North American craton.

Tectonic transport is the logical vehicle for formation of the tectonic element represented by map unit two oceanic crust (Pennsylvanian, Permian, and Lower Triassic—Wheeler, et al., 1972). Its development between the Alexander terrane and the North American craton offers one solution to the problem of why the Alexander terrane (Berg, et al., 1972) or allochthon (Jones, et al., 1972) occurs. The allochthon includes rocks at least as young as Upper Triassic and appears to have moved, possibly intermittently, during the period from the Mississippian until at least the Upper Triassic. Berg, et al. (1972) imply that movement should have ceased by the Upper Jurassic because strata of this age (their Gravina-Nutzotin belt) overlie allochthonous Paleozoic crust that does not itself appear tectonically transported. Tectonic transport may actually have ceased by the time of the Middle Jurassic Columbian orogeny (Wheeler, et al., 1972). The absence of large-scale batholithic plutonism from the Mississippian to the Middle Jurassic therefore is significant.

Paleozoic rocks attached to the western margin of the craton (map unit one), where they are in contact with the Triassic and Lower Jurassic (Nicola-Takla-Hazelton of map unit three, Fig. 32) display an outcrop pattern typically found in rift margins. Fox (1975) cites additional evidence of rifting during the Takla alkalic volcanic episode. The contacts suggest a high probability that initial separation of the allochthon was by rifting, although much later displacement clearly appears to have been accomplished at least partially by right lateral movement on several of the strike-slip faults known to have developed prior to the Tertiary. The association of alkalic plutonism, volcanism, and large-scale normal faulting implies that a period of Lower Mesozoic distentional tectonism largely in a marine environment developed during this period of strike-slip tectonics. Preto (1975) also cites evidence that Triassic rift structures that were developing concomittantly with Nicola volcanism (map unit three of Fig. 32) were compatible with strike-slip tectonics for adjacent terranes.

K-Ar dating of the long, but less than 8 km (5 mile) wide band of blue schist metamorphic facies rocks within the Pinchi fault have indicated ages from 216 to 211 m.y. (Paterson and Harakal, 1974). The regional geologic setting clearly suggests that strike-slip movement took place on this high angle fault during metamorphism, although Paterson and Harakal (1974) mention the possibility of thrusting. The high-pressure low-temperature mineralogy of the rocks could have formed under either strike-slip or thrust conditions but the case for dextral fault displacement is easier to understand in light of evidence cited by Preto (1975) and Fox (1975).

The Paleozoic-Precambrian rocks of Washington's Cascades (included as group 1a in Fig. 32) are bounded on the east by formations lithologically identical to and of the same age as the Cache Creek-Hazelton-Takla-Nicola groups that separate the Alaskan Paleozoic allochthon from the North American craton. Should presently undated metamorphic rocks along the west margin of British Columbia's Coast Range plutonic complex and between the Alexander allochthon and the Cascade Paleozoic eventually be shown to include Paleozoic rocks, then the Paleozoics from the Cascades to Alaska may be demonstrated as one large allochthon.

The allochthonous crust differs from strata of the same age that forms part of the nearby North American craton. The allochthon has been displaced northwesterly relative to the craton. It also represents the continental margin accumulations, whereas the craton contains more typical shelf and platform strata.

Porphyry copper deposits that formed in the interval 205-170 m.y. therefore developed at the end of a long period of plate distension. Included with these deposits are all of the diorite and most of the granitic pluton type. Within this period of Lower Mesozoic distensional tectonics, only diorite and granitic pluton type deposits are known to have formed. These developed comagmatic with their extrusive hosts as volcanic centers. The conditions of rifting described by Fox (1975) and Preto (1975) for the porphyry environment were preceded by a long history of rifting and strike-slip faulting.

Studies in Alaska that are cited in this volume indicate that marine volcanic accumulations now located along the continental margin and south of the Denali fault of Pennsylvanian to pre-Upper Jurassic age also may be in part allochthonous with respect to the North American craton. These orogenic accumulations added to the continental margin (the Taku-Skolai terrane of Berg, et al., 1972) are identical to and are coeval with some of those pre-Upper Jurassic extrusives and sediments found in the Insular belt of Monger, et al. (1972), which includes Vancouver Island.

The Island Copper porphyry deposit is associated with a stock and dikes within a major shear zone. Movement on this shear appears, based on regional geology, to be right lateral and sulfide mineralization occurs in an elongate pattern within the shear beyond the Island Copper deposit. Superficially, at least, it appears that intrusion, mineralization, and displacement on the dextral fault were overlapping. This deposit, with a 153 m.y. date, would seem to have formed during a period of San Andreas type fault activity during which tectonic transport of the allochthon occurred.

In the post 80 m.y. period strike-slip tectonics were again dominant following relaxation of strong regional compression (Monger, et al., 1972). As noted previously, however, where Tertiary porphyry deposits developed in Lower Mesozoic volcanic terrane they formed as stock-type porphyry copper deposits. The type of crust penetrated by the mineralized intrusion apparently exerted significant control over its metallogeny. The absence of rift tectonics in the Tertiary coincides with an absence of Tertiary diorite porphyry copper deposits. The diorite model occurs only in association with persistent normal faults of the Lower Mesozoic.

Fig. 33 shows the location of porphyry molybdenum (after Clark, 1972) as well as porphyry copper deposits in such a manner that their spatial distribution may be appreciated.

TYPES OF PORPHYRY DEPOSITS IN THE CANADIAN CORDILLERA

Different crustal settings have been accompanied by three distinct types of porphyry copper deposits. Examples of the diorite, granitic pluton, and stock types are described in that order.

The Diorite Model

Definition of Diorite Model Porphyry Copper Deposits: The diorite model is defined as a quartz-deficient, commonly zoned, diorite-monzonite-syenite pluton with pervasive alteration and disseminated sulfide copper occurring in or concordant with the diorite, monzonite, or syenite phase. Petrographic zoning may be absent so a diorite could host the sulfides alone; if so, the diorite may be alkalic or calc-alkalic. Diabase may provide a similar response to the action of hydrothermal fluids, as may extrusive equivalents of the diorite-monzonite-syenite suite, so these rocks are included in the model.

Petrographic variations from diorite to syenite of the rocks that host individual diorite model porphyry copper deposits lead to great differences in silicate alteration mineral assemblages within the model. Generalizations concerning petrography, alteration, and mineralization are made and followed by specific examples of soda-potash (Ingerbelle-Copper Mountain), sodic (Afton), and potassic (Galore Creek) deposits. Diorite model deposits have been found in the Pennsylvanian-Permian-Triassic marine volcanic formations of Alaska but none has yet proven commercial. These deposits therefore could occur from Alaska to the Idaho batholith, where upper Paleozoic-Lower Mesozoic marine volcanic rocks occur. Most importantly, however, the diorite porphyry copper deposits occur within three elongate belts in British Columbia (Fox, 1975) within the Nicola-Takla-Hazelton formations. All examples cited in this chapter are from British Columbia.

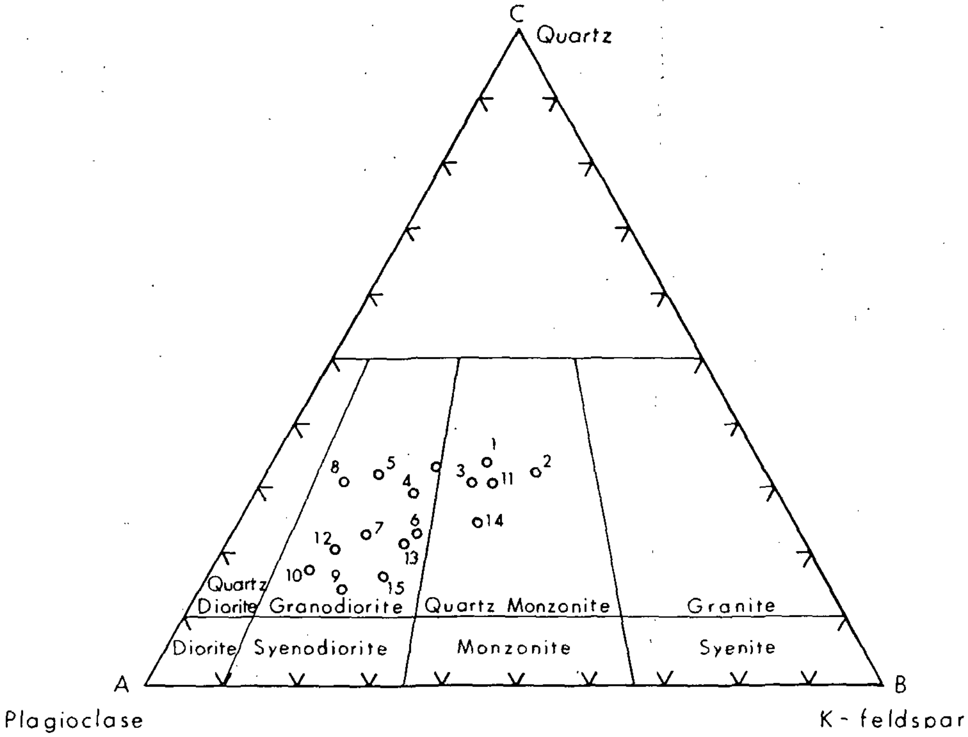
Petrography and Alteration in the Diorite Model: Sutherland Brown, et al. (1971) and Field, et al. (1974) indicate that the diorite model actually includes syenites, monzonites, alkalic gabbro, and other quartz-deficient intrusions in addition to diorite. Most phases in the intrusive sequence are typically porphyritic. Fox (1975) encourages the speculation that most dioritic rocks are part of either nepheline or leucite normative alkalic magma series distinct from the calc-alkaline suite that gives rise to quartz-bearing intrusions, a discussion further refined in *CIM Special Volume 15* (1976). This petrochemistry is summarized in the ternary diagram of Fig. 36b.

Undersaturated intrusions other than diorite could derive from a dioritic parent by potassic metasomatism, through processes of assimilation or differentiation, or some combination of these. However, the occasional presence of magmatic(?) garnet, nepheline, analcite, leucite, and other minerals not characteristic of calc-alkaline intrusions supports the hypothesis that they are a distinct magmatic series. Similarly, the time relationship between early diorite and late syenite in each zoned porphyry copper-bearing magmatic sequence suggests the two are genetically associated in composite zoned differentiated intrusions.

The unifying feature of the quartz-deficient intrusion that hosts porphyry copper mineralization regardless of magmatic composition is the fairly uniform response of the rock to sodium, potassium, and hydrogen metasomatism. In most deposits a potassic zone is surrounded by a chlorite-dominant propylitic zone. If sodium metasomatism developed instead of potassium the potassic zone may not appear. The mineral assemblages in the propylitic zone may vary widely in detail from deposit to deposit, but if a potassic zone has developed it is always dominated by chlorite- or biotite-rich assemblages or both. In only a few deposits is a phyllic or an argillic zone developed. Rather, a central potassic zone tends to pass directly to the outer chlorite-rich propylitic zone with no intermediate stages developing, in contrast to the silica-rich porphyry copper deposits (quartz monzonites) described by the Lowell and Guilbert (1970) model of potassic-phyllic-argillic-propylitic zoning from the core outward. The pyrite halo in the diorite model may be greatly diminished in both volume and intensity compared to the more silicic model.

With only two alteration zones generally discernable in diorite deposits within the terms of the Lowell and Guilbert (1970) alteration zone definitions, copper is less uniformly fixed in any one zone. It may occur in what is mineralogically a propylitic zone, as at Duckling Creek, or in the potassic zone, as at Galore Creek. Metallization may also occur in both potassic and propylitic zones or in the phyllic zone in the rare instances of its presence. This results in a weakened reliance on zoning as an exploration tool in the search for a copper center, which usually includes the potassic zone if present but is not restricted to this.

Sodium metasomatism has been reported at Afton (Iron Mask batholith) and Ingerbelle (Copper Mountain stock) but mineralogy of this alteration suite has not been well documented. The Copper Mountain stock contains a porphyry copper deposit associated with a potassic center (the Copper Mountain ore body) as well as one associated with a sodium metasomatism (the Ingerbelle ore body). Sodium metasomatism has also been recognized by Hollister, et al. (1975),



1. Maggie
2. Casino
3. Island Copper
4. Ox Lake
5. Catface
6. Brenda
7. Granisle
8. Morrison
9. Newman
10. Bond Creek
11. Berg
12. Fish Lake
13. Shaft Creek
14. Berg
15. Poison Mtn.
16. Huckleberry

Fig. 36a. Petrography of stock type deposits. Modal and normative compositions from fresh rock in porphyry complexes where available in the literature are shown in this figure. Because fresh rock analyses are used the composition given is not that ordinarily found spatially and temporally close to ore and composition does not reflect the phase that accompanies ore (*modified after Carter, 1974*).

in diorite model porphyry deposits in Alaska.

Mineralization in the Diorite Model: Mineralization in diorite model porphyry copper deposits tends to occur most commonly in spatial association with monzonite or syenite phases of zoned diorite-monzonite-syenite intrusions. Copper sulfide is accompanied only rarely by molybdenum but commonly by abnormally high gold:copper ratios. Sulfur accompanying the copper is insufficient to consume the iron present in the host intrusion, and the altering mineralizing process leaves large amounts of magnetite accompanying chalcopyrite. Magnetite may be as important a hydrothermal mineral in dissemination in diorite model porphyries as is pyrite in quartz monzonite model deposits, occurring as a dissemination in the potassic and propylitic zones. Mineralizing fluids appear to be silica-deficient because

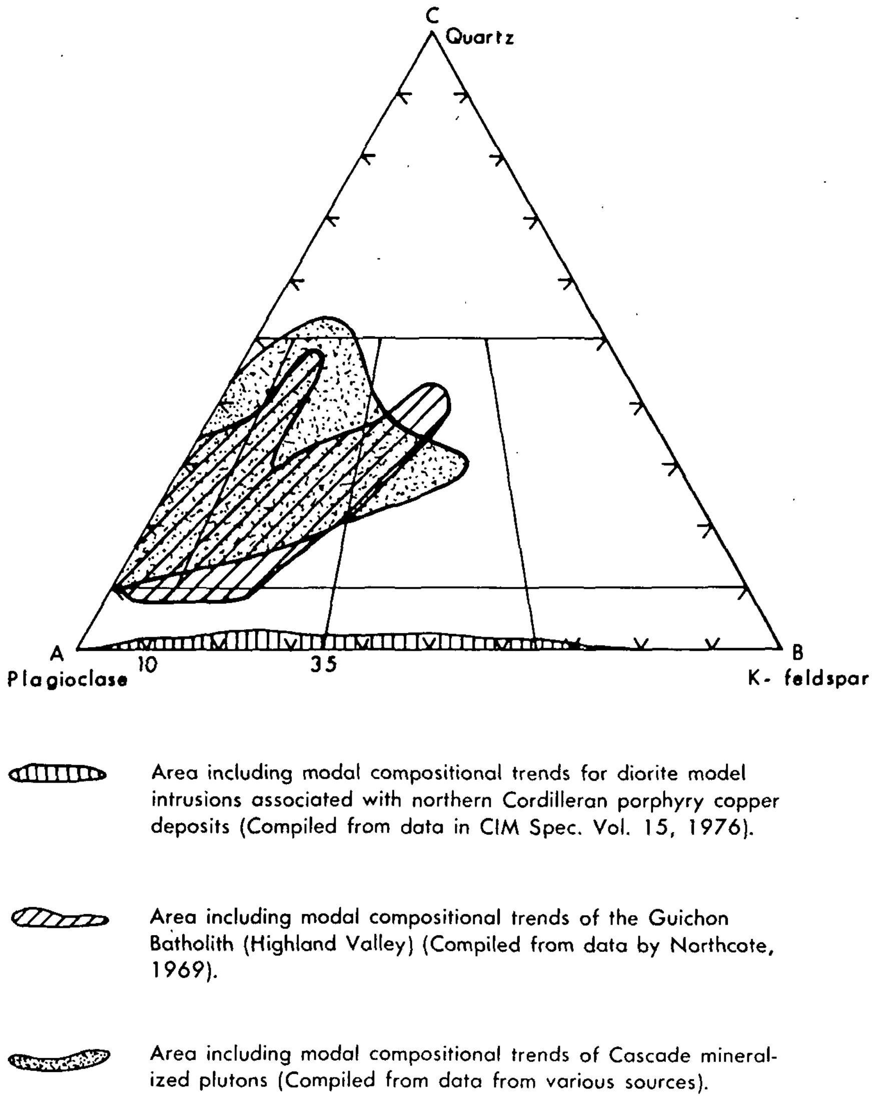


Fig. 36b. Petrography of diorite, granitic pluton, and Cascade deposits. Compositional trends for plutons associated with diorite model porphyry copper deposits are compared with trends for plutons associated with continental margin deposits and the Guichon batholith. The Cascade trends are believed typical of continental margin belts underlain by oceanic crust and are similar to trends established for the Antilles.

veinlets containing the ore sulfide may be free of quartz but may contain epidote, chlorite, calcite, prehnite, or zeolite.

Stockworks are much more common in diorite model porphyry copper deposits than breccias. Volumetrically, dissemination of ore minerals in the potassic zone is important in most intrusions, while fracture filling is most important in zones adjacent to the potassic.

Fox (1975) cites examples of the diorite type porphyry deposits where a central biotite zone carrying chalcopyrite-bornite-magnetite or bornite-magnetite gives way to a peripheral zone of chlorite-epidote-albite with associated pyrite-chalcopyrite. Gold is concentrated in the bornite-magnetite zone in some deposits.

Zinc and lead occurrences attributed to zoning are rare in a copper-zinc-lead sequence around the copper heart of diorite deposits. The diorite model does not seem to occur in a zoned district.

Ingerbelle-Copper Mountain: A Diorite Type Example: The Ingerbelle-Copper Mountain complex is a fairly typical diorite model deposit. Since it was discovered in 1884 and was the first porphyry copper deposit mined in British Columbia, a substantial bibliography exists describing its geologic features. This summary, however, emphasizes selected features from the description given by Ney and Brown (1972). The Ingerbelle ore body has a reserve of 69 million mt (76 million tons) of 0.53% Cu.

In the Ingerbelle-Copper Mountain area a complex zoned diorite-monzonite-syenite pluton with a radiometric date of about 193 m.y. intrudes Nicola group (map unit three in Fig. 32), which is composed of fragmental marine andesites, water-laid tuffs, and volcanic siltstones. Except in the immediate vicinity of the plutonic rocks, deformation, metamorphism, and metasomatism are very mild.

The intrusions found in and near ore are quartz-poor, porphyritic syenite in composition, and albitized. They are popularly regarded as genetically related to the Copper Mountain stock through differentiation, although surface outcrop is inadequate to clearly establish this. The close spatial relationship between igneous rocks and ore has led to the common assumption that a genetic relationship also exists.

Mineralization has been accompanied by potassium, sodium, hydrogen, and sulfur metasomatism. Within 60 m of the Copper Mountain stock, hydrothermal alteration has overprinted a granoblastic development of diopsidic pyroxene, hornblende, biotite, epidote, and intermediate plagioclase. Hydrothermal alteration has developed in several successive stages. Development of a biotite rich but orthoclase-poor potassic zone appears to have been the earliest stage but this has been largely obliterated by successive hydrothermal events. The early potassic zone was probably widespread as remnants are found at widely separated localities. Magnetite formed intergrowths with the biotite. Orthoclase is common only near Copper Mountain. The remaining biotite zone includes the Copper Mountain ore body. Within the potassic zone, an assemblage of albite, epidote, sphene, apatite, and minor pyroxene succeeded development of pervasive biotite along some fractures and areas of fracturing. Although not district-wide in its appearance, this type of alteration has converted some andesite to megascopically appearing diorite-textured andesite.

Scapolite, albite, calcite, chlorite, and other hydrated iron silicates make up the last stage of alteration. The scapolite-chlorite assemblage replaced part of the biotite zone as well as apparently fresh rock. It surrounds the potassic zone and is popularly considered equivalent to the propylitic zone. The scapolite-chlorite assemblage includes the Ingerbelle ore body.

Within the Ingerbelle ore body albite, chlorite, and carbonate are more important than quartz as gangue occurring with ore sulfides.

From the sequences noted it is clear that a quartz-sericite dominant phyllic zone is not important in this area. Hypogene copper sulfide mineralization is found in what was the early potassic alteration phase as well as in alteration assemblages peripheral to and replacing it. If the albite-scapolite alteration assemblages may be termed propylitic, then the propylitic zone occurs adjacent to and probably replaced part of the potassic and contains significant hypogene copper sulfide. Within these definitions the Copper Mountain ore body was found largely in the potassic alteration zone, whereas the Ingerbelle occurs largely in the propylitic.

Afton: A Sodium-Rich Diorite Model Example: Afton has been described by Carr (1976) as a steeply dipping 27 million mt (30 million ton) ore body containing 1% Cu that occurs at the west side of the nepheline-normative 198 m.y. Iron Mask batholith. This is a zoned pluton with diorite, monzonite, and syenite stages, with ore occurring near a syenite outcrop. The ore minerals show a vertical and lateral concentric zoning outward from a core containing native copper through chalcocite to bornite, then chalcopyrite, and finally to pyrite outer and lower zones. The extent of iron oxidation increases markedly with increasing alteration and accompanies the economically important copper mineralization, leading Carr (1976) to conclude that the native copper formed as a result of supergene processes.

Alteration minerals accompanying the different copper zones suggest extensive aluminum and sodium metasomatism. The zonal pattern of the gangue and ore minerals grades outward from a core with goethite-prehnite-albite-chlorite-chalcocite-native copper downward and laterally through albite-epidote-chlorite-hematite-bornite-chalcocite, albite-chalcopyrite-bornite-chlorite, to an erratic outer pyrite-magnetite bearing phase. A chlorite-rich propylitic zone surrounds the pyrite-bearing halo.

Quartz and molybdenite are notable for the rarity with which they are found to fill fractures.

The inferred composition of the ore fluid based on the mineralogy present suggests influence by alkalic undersaturated rocks.

The ore occurs in veinlets and as a cement for breccia of altered host rocks. The suggestion implied by repetitive veining and brecciation is that openings that reappeared over a considerable time span became filled with vein matter deposited at successively lower temperatures. Alteration mineral zoning appears compatible with that described in the McCarthy and Jacobsen (1976) model.

Galore Creek: A Potassium-Rich Diorite Model Example: The Galore Creek deposits described by Barr (1966) are ten hypogene cupriferous sulfide concentrations localized in highly fractured and altered Triassic intrusive and extrusive rocks. The intrusions are parts of a potassium-rich syenite complex, and the deposits, which occur over an area 3.2 x 5.6 km (2 x 3.5 miles) may be separated into either porphyry copper or pyrometasomatic types.

The syenite consists of a number of phases rich in orthoclase and poor in mafic minerals. None contain as much as 5% modal quartz. Feldspathoids have been identified in some units.

Both extrusive fragmental and cataclastic breccias occur within porphyry copper deposits in the complex. In areas where potassium metasomatism has not been too severe breccia fragments are clearly discernible and the character of fragmentation permits classification as to type. However, contacts between various units of the complex are frequently masked by intense alteration and in most cases the origin of a breccia cannot be distinguished with any degree of certainty. Sulfide occurs as a cementing mineral in breccias clearly of cataclastic origin.

Within copper sulfide-bearing areas the most consistent and directly asociated secondary silicate encountered is biotite, which generally occurs as a fine-grained felted mass and may make up 50% of the rock. Most mineralized zones also contain orthoclase as veinlets and massive replacements commonly associated with biotite where sulfide is present. Anhydrite, garnet, magnetite, and apatite may occur in this potassic zone but without a consistent spatial relationship to sulfide. Pyrite is pervasive in the potassic zone. All major units of the complex are propylitized if potassic (biotite-orthoclase) zone alteration is not present. Epidote, chlorite, and lesser sericite replaced the original magmatic silicates in the propylitic zone. Alteration zoning therefore consists of potassic-propylitic with copper strongest in the potassic core.

Quartz Monzonite Model Granitic Pluton Type

Granitic pluton type porphyry copper deposits (after Field, et al., 1974) occur associated with zoned quartz diorite-granodiorite-quartz monzonite intrusions of batholith size, with porphyry deposits frequently occurring in the interior or core associated with the youngest phase. These plutons occur from the Cuddy Mountain-Peck Mountain area in Idaho, as noted by Field, et al. (1974), to the Gibraltar deposit in British Columbia. All are intrusive into the Triassic-Jurassic Takla-Hazelton-Nicola volcanic assemblage or its equivalents in Idaho and Washington and commonly are comagmatic with their host. With the possible exception of Brenda with its inconclusive K-Ar date, no granitic pluton deposits have been found with dates appreciably younger than the intruded calc-alkalic volcanic rocks. All appear to occur in the 205-170 m.y. range except Brenda. Table 12 lists the largest known ore deposits of this type.

Petrography in the Granitic Pluton Type: The granitic plutons that host porphyry copper deposits are upper mesozonal to epizonal multistage intrusions containing concentric phases with early, more mafic nonporphyritic and sheared quartz diorite margins and younger more silicic, alkaline, and porphyritic cores. The most common magmatic terminal phase is close to quartz monzonite in composition. Petrography of this type is shown in the ternary diagram of Fig. 36b.

Northcote (1969), Ager, et al. (1972), and Hylands (1972) make an excellent case for magmatic differentiation in the Guichon batholith and their petrographic interpretations are applicable to other plutons (e.g., Cuddy Mountain, Gibraltar) similar to the Guichon. Their strongest evidence is the gradational contact that may be seen between any two adjacent petrographic stages. Acceptance of this hypothesis permits speculation that mineralization may be an end product of differentiation of a calc-alkalic magma and the evidence is continuous enough to be plausible. The most effective process of differentiation appears to have been inward residual enrichment of alkali and silica in the crystallizing magma.

Structure and Mineralization: Sulfide regularly occurs in the core zone closely allied with the youngest intrusive phase, adding support to the differentiation-mineralization concept wherein as the core unit crystallized, confining pressure was exceeded by increasing internal pressure, and hydrothermal fluids escaped in silicate-silica-sulfide breccia pipes, dikes, and stockworks. Existence of late dikes occurring with stockwork copper-molybdenum deposits suggests a common origin and emplacement control for both. In the individual ore bodies, stockworks that trend with the major faults cutting the batholith dominate.

Hollister, et al. (1975) suggest a structural control at Highland Valley for evolution of the pluton (from early quartz diorite to late quartz monzonite), alteration from early potassic to late phyllic, and mineralization (beginning comagmatic with late granodioritic intrusions subjected to potassic alteration and ending with late quartz monzonite intrusions, some of which have phyllic alteration associated with ore). The timing of events based on their fault reconstructions provides continuous link between wholly magmatic events and magmatic events that accompany hydrothermal activity. Their fault reconstructions interpret the mineralization stages to coincide with magma ranging from granodioritic to quartz monzonitic in composition. In this reconstruction the ore bodies that appeared early are clothed in a potassic alteration suite, whereas the later ones occur in an extensive phyllic zone. Fig. 37 illustrates the structural developments at Highland Valley.

Drummond, et al. (1972), show that sulfide mineralization occurs surrounding the quartz-feldspar porphyry core of a zoned intrusion at Gibraltar. Their evidence is compatible with derivation of the sulfide from a large differentiating calc-alkalic pluton.

Soregaroli (1971) describes mineralization at Brenda in what he calls a zoned and composite intrusion. The general setting appears similar to that found in the Guichon, although Brenda mineralization occurs at the point of contact between the pluton and the intruded rock.

Table 12 lists the alteration zoning sequence from the center outward. All samples cited have a well developed potassic zone and most have well defined phyllic zones. An argillic zone developed in only a few High-

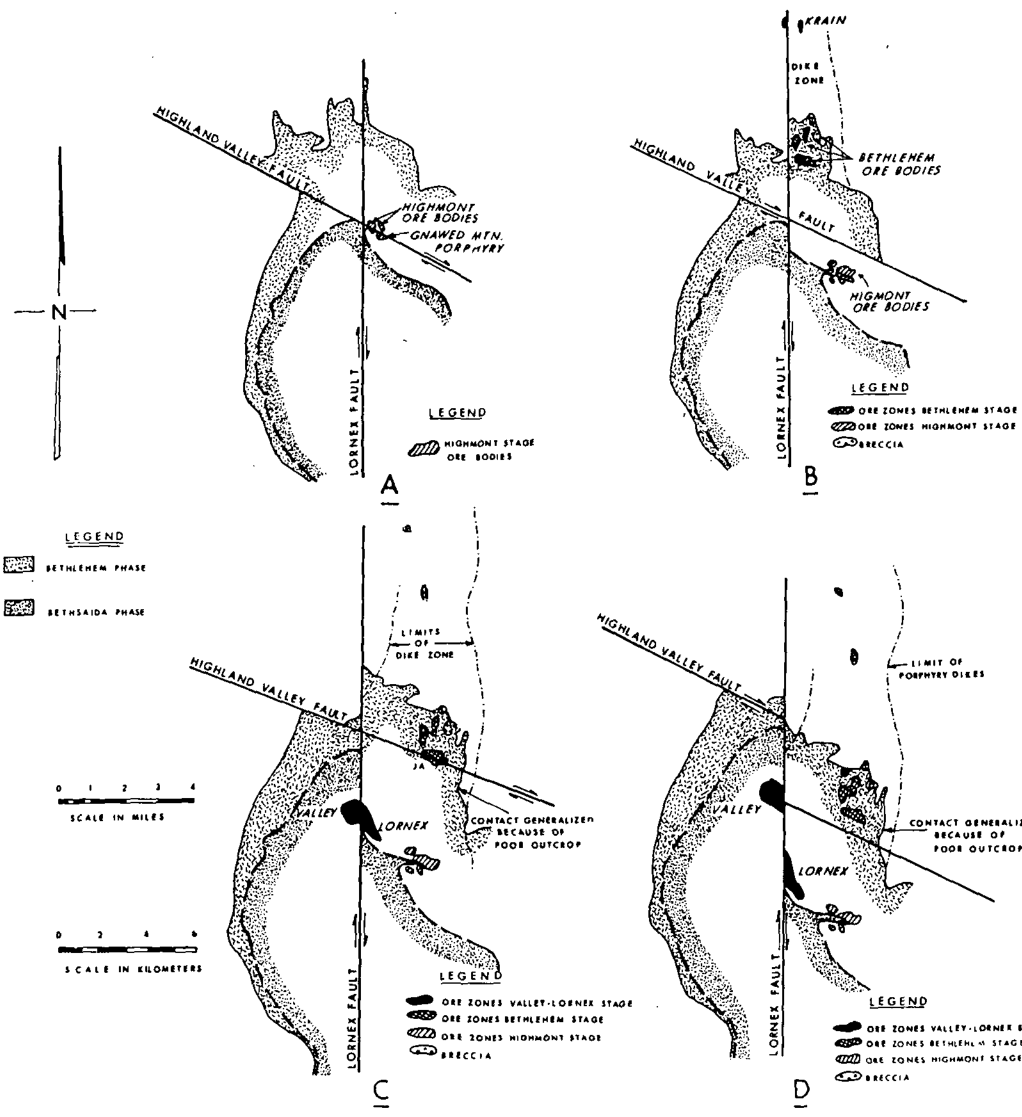


Fig. 37. Structural evolution of the Highland Valley. Movements on the Lornex and Highland Valley faults occurred simultaneously and alternatively in the final phases of intrusion of the Guichon batholith. The fault planes provided the openings for the admission and deposition of mineral and igneous matter. Displacements on these two major faults permitted a dilation of the host rocks by an order of 20%, as indicated by the amount of dikes and vein material now present that constitute the ore bodies. The earliest stage of hydrothermal activity appears to have been in and close to the Highmont ore body, which has the lowest copper-molybdenum ratio in the district. This ore body (**Fig. 37A**) formed as soon as consolidation of the differentiating pluton had advanced to the point where walls were strong enough to support openings at and near the junction of the two faults. **Fig. 37B** shows the configuration of the batholith at the end of the formation of the Bethlehem ore bodies. Displacement of various fault blocks infers simultaneous confined movement on both the Lornex and Highland Valley faults from the time of Highmont mineralization through the development of all Bethlehem ore bodies. The Bethlehem ore bodies formed in

land Valley ore deposits (i.e., Lornex deposit) but is missing in the other examples. Pyrite zones around this type of porphyry copper deposit are usually erratically developed—i.e., they do not extend far beyond the ore body, do not ordinarily contain more than 3% pyrite, and the area containing disseminated pyrite ordinarily includes large areas of rock barren of pyrite.

A substantial percentage of the ore sulfides in potassic zones are disseminations in the granitic pluton type, whereas fracture filling of sulfides clearly dominates in those zones adjacent to the potassic. No significant copper or molybdenum sulfides are found outside the argillic zone.

Copper may occur in both the potassic zone, characterzied by orthoclase-biotite or orthoclase-chlorite mixtures or both, and in the phyllic zone, essentially a quartz-sericite-pyrite mixture. Chalcopyrite is the dominant copper mineral and copper sulfosalts are rare in most deposits. All ore zones carry some molybdenum. Zinc and lead may be zonally arranged about the copper center.

Quartz Monzonite Model Stock Type

The stock type porphyry in the area of interest is a mineralized boss, dike zone, or stock of calc-alkalic composition injected into its host rock. The mineralized pluton may be quartz diorite to quartz monzonite in composition, but quartz monzonite is the most common igneous stage intruded close to ore in time.

Burchfiel and Davis (1973) point out that igneous intrusions of this type may be structurally anologous to salt plugs intrusive into sediments. Gussow (1962) reaches a similar conclusion for igneous masses. The different structural types suggested by Sutherland Brown (1972) and the examples given by Carson and Jambor (1974) in the Babine Lake area for porphyry copper deposits associated with smaller intrusions suggest that in many places the magma is an igneous piercement or diapir intrusive into wall rock that yielded as injection took place.

Distribution of porphyry copper prospects having a potential in excess of 18 million mt (20 million tons) of 0.1% and displaying porphyry type alteration is shown in Fig. 35. Most fall within the stock type classification. As noted in Table 13, most intrude the Triassic-Jurassic volcanic rocks, although most postdate these extrusives and are innocent of the tectonic environment present during that older period of volcanism.

The majority of stock type porphyries are under 83 m.y.; only a few (e.g., Island Copper) are older. The tendency of these mineralized intrusions to occur during periods of time when formation of batholiths was minimal suggests that they may have a magmatic origin distinct from that which gave rise to the large intrusive masses associated with rapid subduction (e.g., Sierra Nevada type batholiths). This negative correlation also suggests that each may occur under differing conditions of plate movement, with batholiths more easily identified with rapid subduction and the diapiric model more closely associated with strike-slip tectonics.

Petrography of the Stock Type: The intrusion most intimately associated with porphyry copper mineralization of the stock type is commonly close to quartz monzonite in composition. Most such intrusions are mixtures of quartz, plagioclase, orthoclase, biotite, and hornblende. All known well mineralized intrusions are porphyritic. Fig. 36a (Carter, 1974) shows petrographic trends of these plutons. Magmatic quartz and ortho-

the various strands of the Lornex fault. Sulfide and gangue silicates occupied these strands as they formed. The results are the breccia and veinlets that make up the ore body. Dike intrusion accompanied mineralization and the ultimate limit of porphyry dikes is shown in Fig. 37D. **Fig. 37C** shows the position of the batholith at the time of Valley-Lornex mineralization, which followed Bethlehem-stage ore deposition. **Fig. 37D** shows present configuration of the ore bodies with the Lornex displaced from the Valley by postmineral movement. Potassic alteration suite minerals dominate in both the Highmont and Bethlehem stages but sericite-rich phyllic is more widespread in the Valley-Lornex stages, suggesting a change in chemistry of the hydrothermal fluids. The Valley has among the lowest molybdenum: copper ratios in the district. The relationship of ore sulfides to dikes indicates that both may have been derived from a differentiating magma. Displaced fault strands are not shown in these figures (*after Hollister and others, 1975*).

clase may be restricted to the groundmass, as at Granisle, or may occur as prominent phenocrysts, as at Berg.

Other intrusive stages may exist in addition to the quartz monzonite, but composition varies from one intrusive center to another. The other igneous stages usually preceded the quartz monzonite with its closely associated mineralization.

Mineralization and Structure: Mineralization could have accompanied, followed, or been active both during and after injection of the igneous rock. The structure that developed as a result of injection may have controlled or dominated contemporaneous or subsequent entrance of hydrothermal fluids. Breccias commonly are developed with this type of porphyry copper. On the other hand, if the stock is intruded into a regional fault zone or line of weakness a stockwork may develop that reflects this governing structure. The principal veinlet trend parallels that of the major fault. Mineralization is always included with later steps in the sequence of igneous and hydrothermal events.

The injection of a stock also frequently results in development of a circular fracture pattern. The fractures may be mineralized to form an annular stockwork containing a major veinlet trend parallel to the intrusion contact.

Alteration zones may not be as simply developed in the stock type as in the granitic pluton. In the case of porphyry copper deposits associated with small injected intrusive bodies, the hydrothermal fluid may have been a lubricant since rocks near the contact of the pluton usually show stronger hydrothermal metasomatism than do the central parts. Should the intrusive contact be the locus of a potassic zone, the phyllic zone may occur both internally in the stock and externally away from it. On the other hand, if the center of alteration is well within the stock the phyllic, argillic, and propylitic zones will occur outside the potassic in concentric shells in either the pluton or the intruded rock or both.

Copper and molybdenum sulfides commonly are best developed in the contact zone. If this is also the potassic zone, dissemination rather than fracture control of values may be significant. Hypogene values weaken away from the contact zone, although the stock itself frequently contains low grade mineralization. Away from the potassic zone the ore sulfides fill either space between breccia fragments or tectonic voids that may be related to either the force of the intrusion or movement on a regional structure. Sulfide mineral zoning also is frequently related to the contact the pluton makes with the intruded rocks. Molybdenum in some deposits is more conspicuous near the contact than in the walls.

A number of deposits have scattered zinc and lead veins occurring outside the copper zone, suggesting that metallogenic zoning may develop around the stock.

This type of porphyry is most commonly copper-molybdenum with relatively low gold values, although copper-gold types are also known.

The Berg: An Example of the Stock Type: The Berg deposit in west central British Columbia has been the subject of numerous short contributions from a number of sources. This geologic outline summarizes pertinent data from the large bibliography available on the deposit, primarily following Sutherland Brown, et al. (1971).

The Berg composite stock is a cylindrical pluton 800 m in diameter with a 50 m.y. K-Ar date. Composition ranges from an older quartz diorite to a younger quartz monzonite porphyry phase. The pluton intrudes the Hazelton group (map unit three in Fig. 32).

Mineralization and alteration are strongest at the contact between the stock and the intruded rock. The annular potassic zone found in and near the contact contains topaz as well as secondary biotite and orthoclase. Hypogene copper and molybdenum sulfides are zoned in and near this potassic zone with a molybdenite zone occurring closest to the stock contact and copper occurring as an annular zone outside it. A thin discontinuous sericite zone rings the potassic zone and both give way to a pyrite-bearing chlorite-rich propylitic zone developed in the Hazelton rocks. Hypogene copper values reach their peak at

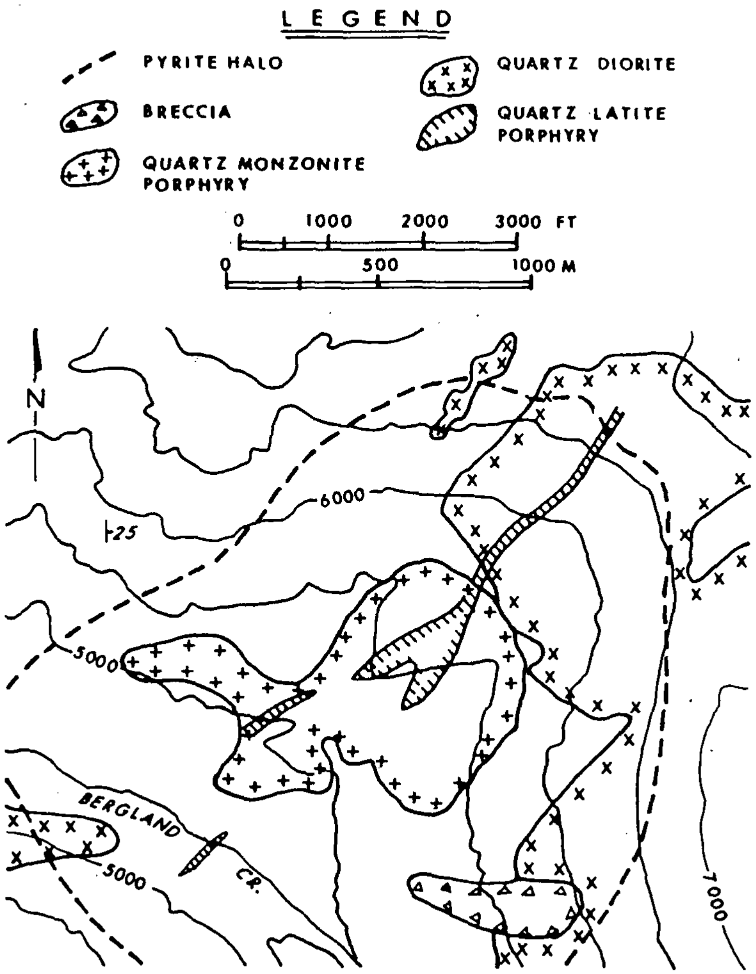


Fig. 38. Geology of the Berg, British Columbia. The Berg quartz diorite-quartz monzonite-quartz latite stock, where sulfide is best developed along and near the margin of the quartz monzonite, is typical of many stock-type deposits. Best grade hypogene sulfide mineralization is found near the north and west contacts of the quartz monzonite (*after Carter, 1974, and Sutherland Brown, et al., 1971*).

the approximate interface of the biotite and chlorite-dominant zones.

The Babine Lake Deposits: Examples of the Stock Type: Carson and Jambor (1974), Carter (1974), and Carter and Kirkham (1969) provide excellent background for summarizing the numerous stock-related porphyry deposits found in and near Tertiary quartz-bearing calc-alkalic plutons acting as diapirs in the Babine Lake area. These stocks are about 51 m.y. in age, intruding rocks of map unit three (Triassic and Jurassic volcanic rocks).

Within the pluton at Bell and Granisle an amphibole zone may be interpreted as the core of alteration and mineralization. Carson and Jambor (1974) point out that hydrothermal amphibole could be paragenetically later than secondary biotite. However, diminishment of copper in this zone coupled with enrichment of copper in the biotite zone (which may surround amphibole) argues that it is a core developed early in the mineralizing process. In mineralized plutons other than Bell and Granisle a central biotite or biotite-chlorite zone usually carries some secondary orthoclase in mineralized plutons where the amphibole zone is missing. Sodic plagioclase is intergrown with orthoclase. Some Babine Lake deposits show a transition from an inner biotite zone to a quartz-sericite-pyrite assemblage (as at Bell and Granisle), whereas some smaller deposits show a direct transition from the biotite to a chlorite-carbonate zone.

In the larger deposits bornite-magnetite or bornite-chalcopyrite mineralization in the potassic zone gives way to chalcopyrite-pyrite and then pyrite as distance is gained from the center of mineralization. Molybdenum grades less than 0.01% Mo and gold is not usually prominent.

Conclusions for Deposits in the Canadian Cordillera

Mineralization in the porphyry copper province of the northern Cordilleran orogen began in the Upper Triassic with what appears to have been a rifting environment. Diorite model and granitic pluton type porphyry copper deposits formed in the Triassic and Lower Jurassic as the trough was filled with volcanic debris. This was followed by a relatively sterile period in the Upper Jurassic and Lower Cretaceous when plutonic activity was batholithic in nature. The Upper Cretaceous and younger periods witnessed a decline in batholithic intrusive activity and a resurgence of smaller stock type porphyry copper-related intrusions. These later deposits tend to be related to circular or oval plutons that may bear a tectonic resemblance to diapirs. They also coincide with development of a strike-slip tectonic regime that became resurgent at the end of the Cretaceous.

What have been called quartz monzonite or calc-alkalic types in this chapter could be incorporated into the Lowell and Guilbert (1970) model if that model were expanded to include the large (e.g., Highland Valley) and small (e.g., Berg) differentiated deposits and if the aberrations in alteration characteristics listed in Tables 12 and 13 also could be accommodated by that model.

The very large granitic pluton types are usually old (Triassic to Middle Jurassic) porphyry copper deposits that have been deeply eroded. Consequently, their alteration zoning and geometric pattern may not fit the typical Lowell and Guilbert (1970) model. Their outlines tend to be governed by the position of copper mineralization in a differentiating pluton of batholithic size. In the case of Highland Valley the aggregate reserves of copper-bearing rock now known exceed 4000 mt and the individual ore zones (e.g., Valley, Lornex, and Bethlehem) have been called fault displacements, as the shapes present are markedly different from the ovals of the Lowell and Guilbert (1970) model.

Such stock type deposits as Berg represent a porphyry copper morphological type that also should be incorporated into the Lowell and Guilbert (1970) model. Mineralization and alteration of the stock type are usually strongest in the vicinity of a stock contact. The resulting doughnut-shaped zone of sulfide still should be considered part of the Lowell and Guilbert (1970) model since petrography, ore mineralogy, and alteration are typical.

Deep erosion at some deposits (e.g., Highland Valley, where the present surface may have been 5 to 6 km below the surface at time of mineralization) may also expose alteration zones that appear to be aberrant from the Lowell and Guilbert (1970) model. The Bethlehem ore bodies, for example, do not have exposed argillic or phyllic alteration assemblages accompanying the potassic zone with its ore minerals. Such zones could have occurred much higher in the system and their absence from some granitic pluton type ore bodies may be a function of depth of erosion alone. The Lowell and Guilbert (1970) model therefore should be modified to include the quartz monzonite (calc-alkalic) model of the Canadian Cordillera.

At the Berg and other similar deposits existence of metallization at and near the contact could be used as evidence for scavenging of metals from intruded wall rock in a meteoric-hydrothermal system generated by heat from a stock. On the other hand, presence of copper-bearing potassic zones within the stocks (e.g., Babine Lake and Highland Valley areas) suggests the possibility that metals were brought in by intrusion. The paucity of molybdenum in the Babine Lake deposits is compatible with their setting (basic marine andesitic volcanic rocks).

PORPHYRY COPPER DEPOSITS OF THE CASCADES

Introduction

Within the Cascades of the northern Cordilleran orogen is a porphyry copper province distinctive in mineralogy, metallogeny, and time distribution. Because of the differences distinguishing these deposits, the Cascades should be treated as a separate province. This section briefly examines characteristics of this province and offers explanations for the differences observed.

The area encompassed by this study extends from 46° to 49° north and is confined to a northeast-trending belt of mineralized plutons found west of the Pasayten fault confined to the area from 120° to 123° west, or an area extending approximately from Yakima to Seattle, WA. East of this province lie the Miocene Columbia River basalts; to the west lies the Tertiary sedimentary and volcanic complex that includes the Olympics. Fig. 39 shows the area covered and Table 14 lists the characteristics of porphyry copper occurrences in this area described in the literature. Although porphyry copper occurrences are common in the Cascades, none of the deposits yet explored are large. Because Table 14 compiles only selected published data, it clearly is not a complete listing of all porphyry copper occurrences in this region. Other deposits are known (e.g., Tabor, 1963) but the compilation in Table 14 adequately summarizes the characteristics of Cascade occurrences.

Geologic Setting of the Cascades

Fig. 39 presents those geologic elements of the Cascades most pertinent to development of this Tertiary porphyry copper province. Thrust faults commonly are not associated with porphyry copper deposits and to avoid cluttering this figure numerous thrusts reported by Misch (1966) are omitted, as are the many formation names. Strike-slip faults and plutons are shown in Fig. 39, however, because these features are closely associated spatially with porphyry copper deposits.

General Geology: Most porphyry copper deposits in this area are Tertiary but their characteristics reflect their setting. The best summaries of geologic setting yet published are by Misch (1966) and McKee (1972). Mattinson (1972) gives excellent radiometric data, while Hutting (1956), Purdy (1954), and Culver and Broughton (1945) provide pertinent data on mineral deposits. Grant (1969) summarized much known data on mineral deposits of the Cascades. This section on general geology selectively abstracts pertinent data important to the development of porphyry copper deposits from these authors. For additional details, the reader should study the references cited.

Crustal Composition: Southwest of the Helena and Deception Creek faults (Gaultieri, et al., 1973, and Grant, 1969) most exposures are Tertiary sedimentary and volcanic rocks with only minor Mesozoic material appearing at the surface. Preponderance of a Tertiary sedimentary and volcanic terrane in this area effectively masks pre-Tertiary crustal evolution, and little may be said at this point about host rocks penetrated by porphyry copper deposits south of these faults.

Oceanic crust is suspected to be a basement underlying a large part of this area (King, 1969). Hill (1975) interprets seismic data to suggest that the volcanic Cascades may not have a significant crustal root.

Between the Helena and Straight Creek faults the most common exposures are of Chilliwack group Devonian to Permian basic marine volcanic rocks, their differentiation products, and their associated volcanogenic sediments. If these rocks are equivalent to part of the Sicker group of the same age and lithology on Vancouver Island, it is conceivable that right lateral movement on the Deception Creek fault and its branches to the northwest may have been about 161 km (100 miles). Most displacement in this speculated correlation between the Sicker and the Chilliwack groups would have to have been pre-Middle Tertiary, as the various Ter-

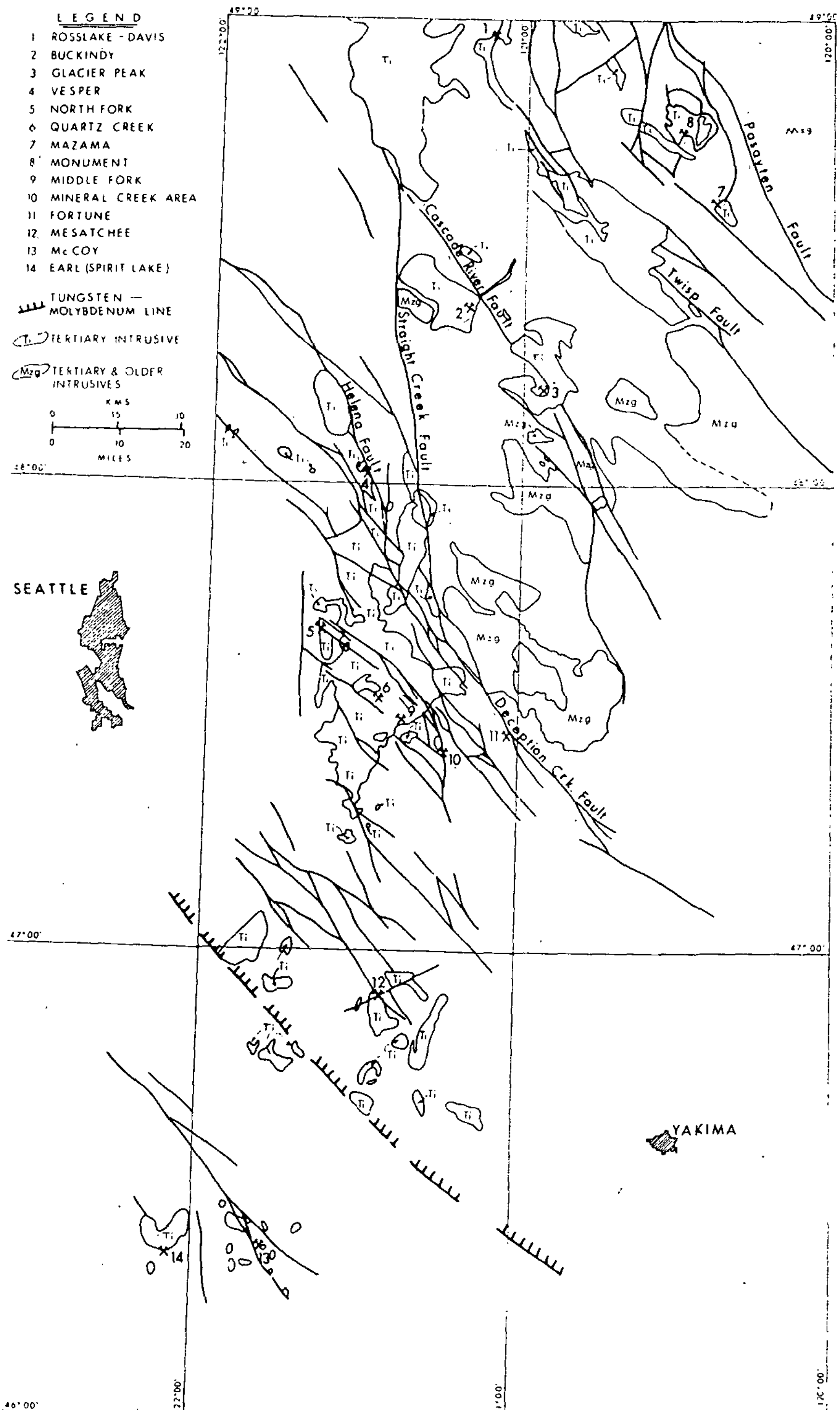


Fig. 39. Structural setting of porphyry copper deposits of the Cascades. Shear couples interpreted for Fig. 33, the compilation of structure of the northern Cordilleran orogen, apply equally to the compilation of strike-slip faults of the Cascades. Thrusts, fold axes, and drainage are omitted to simplify the diagram (*compiled from various US Geological Survey maps*).

Table 14. Tertiary Porphyry Copper Occurrences of the Cascades

Map No.	Name in Literature	Location	Type	Pluton Age m.y.	Host Rock	Alteration Zoning Sequence from Center	Pyrite Zone: Size, m x 10^3 (10^3 x ft)	Pyrite Zone: Content in Phyllic Zone (%)	Structure Model	Major Fracture Trends	Metals Present	References
1	Ross Lake-Davis	121°08′; 48°58′	Qtz Dio Por	30	Tert Vol	Pot-Phy-Arg-Prop	1.2 x 1.2 (4 x 4)	4	Stockwork	NE-EW	Cu, Mo	Grant, 1969
2	Buckindy	121°11′; 48°22′	Grdr Por	—	Pal Gn	Pot-Phy-Arg-Prop	1.8 x 1.5 (6 x 5)	3	Stockwork	EW-NE	Cu, Mo, W	Grant, 1969
3	Glacier Peak	120°56′; 48°12′	Qtz Mon Por	22(?)	Pal Gn	Pot-Phy-Arg-Prop	2.1 x 1.5 (7 x 5)	5	Stockwork	EW-NE	Cu, Mo, W	Grant, 1969
4	Vesper	121°31′; 48°02′	Grdr Por	32	Pal Gn	Pot-Phy-Arg-Prop	1.2 x 1.2 (4 x 4)	3	Breccia	—	Cu, Mo, W	Grant, 1969
5	North Fork	121°37′; 47°37′	Qtz Dio Por	9.9	Tert Sed	Pot-Phy-Prop	—	Po	Stockwork	NW-NE	Cu	Patton, et al., 1973
6	Quartz Creek	121°29′; 47°35′	Qtz Mon Por	18	Tert Sed	Pot-Prop	1.2 x 0.9 (4 x 3)	—	Breccia	—	Cu, Mo, W	Grant, 1969
7	Mazama	120°22′; 48°36′	Qtz Dio Por	70	Cret Sed	Pot-Phy-Arg-Prop	1.5 x 1.5 (5 x 5)	3	Stockwork	—	Cu, Mo	Huntting, 1956
8	Monument	120°29′; 48°46′	Qtz Mon Por	49	Cret Sed	Pot-Phy-Arg-Prop	1.5 x 1.5 (5 x 5)	4	Stockwork	—	Cu, Mo, W	Eaton and Staatz, 1971
9	Middle Fork	121°22′; 47°29′	Qtz Mon Por	18	Tert Sed	Pot-Phy-Prop	4.6 x 1.2 (15 x 4)	4	Stockwork	NW-NE	Cu, Mo	Grant, 1969
10	Mineral Creek	121°15′; 47°25′	Grdr	Tert	Tert Sed	Pot-Phy-Prop	1.5 x 0.9 (5 x 3)	Po	Stockwork	EW-NW	Cu, Mo, W	Grant, 1969
11	Fortune	121°04′; 47°27′	Dac Por	Tert	Cret Sed	Pot-Phy-Prop	1.8 x 1.2 (6 x 4)	4	Stockwork	NW-NE	Cu, Mo, W	Gaultieri, et al., 1973
12	Mesatchee	121°24′; 47°50′	Dac Por	6.2	Tert Sed	Pot-Phy-Arg-Prop	—	Po	Stockwork	NW-NE	Cu, Mo, W	Simmons, et al., 1974
13	McCoy	121°47′; 46°22′	Qtz Dio Por	24	Tert Vol	Pot-Phy-Arg-Prop	1.2 x 1.2 (4 x 4)	Po	Stockwork	NW-NE	Cu	Huntting, 1956
14	Earl (Spirit Lake)	122°05′; 46°21′	Qtz Dio Por	16	Tert Vol	Pot-Prop (Tour)	1.8 x 1.2 (6 x 4)	—	Stockwork	NW-NE	Cu	Huntting, 1956

Tert: Tertiary
Qtz: Quartz
Dio: Diorite
Por: Porphyry
Mon: Monzonite
Cret: Cretaceous
Sed: Sediments
Gn: Gneiss
Vol: Volcanics
Dac: Dacite
Grdr: Granodiorite
Pal: Paleozoic
Pot: Potassic
Phy: Phyllic
Arg: Argillic
Prop: Propylitic
Po: Pyrrhotite

tiary plutons do not appear to be offset by this fault system.

Pre-Devonian crystalline rocks outcrop between the Straight Creek and Helena faults, including the Yellow Astor gneiss with its Precambrian radiometric dates (Mattinson, 1972, and Misch, 1966). Although much of the exposed pre-Devonian consists of thrust slices overlying the Devonian-Permian Chilliwack group, allochthonous outcrop of these older rocks to the northwest favors existence of a pre-Devonian cratonic basement for this segment of the Cascades.

Between the Straight Creek and Deception Creek faults on the west and the Cascade River fault (Tabor, 1963) on the east, the crust consists of pre-Mesozoic gneisses invaded by Mesozoic and Tertiary plutons. Yellow Astor gneiss in this area includes Precambrian; however, the only clear dating for most of these rocks is unquestionably pre-Jurassic. However, most gneisses are believed to be metamorphosed Paleozoic formations. Whatever its age, the present metamorphic complex with large Mesozic and Tertiary batholiths occupying nearly half of the area simulates cratonic crustal conditions. The metamorphic terrane east of the Straight Creek fault is similar to another terrane to the north, on the west side of the northerly projection of this fault. The relationship has led to speculation that pre-Upper Cretaceous right lateral displacement on the Straight Creek fault is 193 km (120 miles) (Misch. 1966).

Gneissic rocks of pre-Upper Jurassic age are dominant between the Cascade River fault and the Twisp fault. Included in this metamorphic terrane are Permian rocks whose lithologies are similar to parts of the Cache Creek formation in British Columbia. Large Mesozoic and Tertiary batholiths intrude this terrane, again simulating cratonic conditions.

Between the Twisp and Pasayten faults (the Twisp and Eightmile fault of Eaton and Staatz, 1971) the rocks are volcanics and sediments of Upper Jurassic and Cretaceous age. These partial equivalents of the Gravina-Nutzotin belt (Berg, et al., 1972) represent the clearest tie between Cascade formations and rocks to the north, since Gravina-Nutzotin belt rocks appear intermittently from Alaska to the Columbia River Plateau.

East of the Pasayten fault is a large complex Mesozoic batholith. The fault itself appears to be a right lateral strike-slip structure with large but undetermined pre-Tertiary movement. The batholith is coeval with some Mesozoic rocks west of the Pasayten fault, suggesting a possible arc-trench-batholith relationship developed in the Upper Jurassic-Lower Cretaceous.

McBirney (1975) summarizes Cascade Cenozoic volcanism. In the porphyry copper province composition of volcanic rocks seems to reflect thickness of the lithosphere. Volcanism of the Cascade Range was concurrent with eposides elsewhere around the Circum-Pacific region and seems to have been independent of subduction rates or other local variables computed from a plate motion. Dating of Cascade porphyry copper deposits (from 6.2 to 49 m.y.) does not conflict with this conclusion.

Structure: Fig. 39 contains the same tectonic elements found in Fig. 34 for the Canadian Cordillera. The northwest trending Pinchi set is well represented in the Pasayten, Twisp, and Deception Creek faults, all of which may have had substantial right lateral movement. The most effective regional tectonic force acting intermittently through parts of the Upper Mesozoic and Lower Tertiary (as interpreted from this fault pattern and the dated igneous rocks cut by the pattern) was the northward movement of the Pacific plate relative to the North American plate. Movement between plates was accommodated by displacement on faults that make up the northwest-trending set.

Fold axes and thrust faults (not shown in Fig. 39) indicate that westward tectonic transport of the North American plate and intermittent eastward-dipping subduction below the plate also were effective in fracturing the North American plate margin. At this time it is impossible to tell which of these two phenomena was most important.

The spatial relationship between strike-slip faults and porphyry copper deposits suggests that the two are probably genetically related.

The strike-slip faults may have provided access to the surface and upper crust for material escaping from depth.

Fig. 39 also shows the southern boundary of Cascade tungsten and molybdenum occurrences (Culver and Broughton, 1945, and Purdy, 1954). This line coincides with the northern limit of the Pacific orogen (King, 1969). Both these lithophiles may be incorporated into Cascade porphyry systems, making porphyry deposits in this region unusual for the Cordilleran orogen. If the tungsten-molybdenum line is accepted as the southern limit of basement cratonic crustal conditions, conceivably porphyry deposits south of the line would differ distinctly from those to the north. Analysis of the statistically small number of deposits presented in Table 14 shows this may indeed be the case.

Porphyry deposits whose descriptions are published and are plotted in Fig. 39 form a northeast-trending zone anomalous to regional tectonic grain (northwest), the physiographic axis of the Cascades (north-south), and to the plate boundary (also northwest). Why these Tertiary deposits trend northeast remains to be explained.

Characteristics of Cascade Porphyry Copper Deposits

Table 14 summaries briefly the various characteristics found in Cascade porphyry copper deposits. Several striking features distinguish this province from porphyry copper provinces elsewhere in the Cordilleran orogen—i.e., the wide variety of both host and mineralized intrusive composition, the generally low sulfur potential of most deposits, the possibility that pyrrhotite may occur significantly in place of pyrite, and the common occurrence of tungsten as scheelite within the porphyry system. These features are examined in detail.

Petrography: Table 14 lists the composition of the intrusion closest to ore (modified from Grant, 1969). All are calc-alkalic and quartz-bearing. In many examples, particularly those north of the tungsten-molybdenum line, the pluton is an intrusive complex containing a dominant premineral quartz diorite phase. The smaller granodiorite and quartz monzonite phases close to mineralization are invariably younger and usually porphyritic. South of the tungsten-molybdenum line, both the pluton and the phase closest to ore (distinguished by textural features) tend to be quartz diorite.

In the quartz diorites many plutons have unusually calcic plagioclases (Grant, 1969). Hornblende is the most common mafic although biotite is also known. Most intrusive phases closely associated with mineralization are porphyritic. Quartz, hornblende, biotite, and zoned plagioclase of average andesine composition are the most commonly occurring phenocrysts, with orthoclase prominent in few deposits.

Where the plagioclase-orthoclase ratios approach one, orthoclase is more common in the groundmass of the porphyry. With plagioclase phenocrysts generally prominent, orthoclase tends to occur as a fine-grained interstitial mineral with quartz.

Alteration: The alteration sequence from the core of each deposit is shown in Table 14. All deposits have a potassic zone. Potassium metasomatism is ubiquitous but its effect varies from deposit to deposit. Some potassic zones are masses of velvety fine-grained secondary biotite with other silicates and sulfides comprising less than 20% of the rock (e.g., Mineral Creek). In others (e.g., Middle Fork) secondary orthoclase is dominant. Grant (1969) presents evidence of as much as 300% K_2O enrichment in the potassic zones in some deposits, but all examples used in his study occur north of the tungsten-molybdenum line. Examples of porphyry occurrences south or west of this line may have only minor secondary orthoclase with the biotite if it is present at all; secondary plagioclase may be the chief feldspar in the potassic zone. Chlorite also occurs erratically in the potassic zones as a hydrothermal mineral with other secondary silicates.

A typical quartz-sericite-pyrite phyllic zone occurs within most deposits. Occurrences with smaller pyrite halos may not have such an alteration assemblage, on the other hand, and the potassic zone may be ringed by a propylitic assemblage. However, where the phyllic zone does occur it is peripheral to the potassic. In all cases, sericite is a fine-grained pervasive silicate occurring with secondary quartz and pyrite.

A kaolin- or kaolin-illite-rich argillic zone appears peripheral to the phyllic zone in more than half the deposits. It varies in size and mineralogy but usually contains pervasive calcite as well as sulfide and clay. Its appearance could be interpreted as evidence of the young age and minimal erosion of deposits in this province.

A chlorite-rich propylitic zone surrounds the other alteration assemblages and also may contain epidote, pyrite, calcite, albite, and other typical propylitic zone minerals. Sulfides are not well developed, however.

Sulfur combining with iron in the potassic, phyllic, and argillic zones of Cascade deposits may develop pyrrhotite-rich halos rather than the typical pyritic halos more frequently seen in deposits elsewhere in the Cordilleran orogen. Pyrrhotite occurs rarely in smaller deposits elsewhere in the Cordilleran orogen (e.g., Battle Mountain). The frequency with which pyrrhotite porphyries are found in the Cascades sets this province apart. Both pyrite and pyrrhotite develop most strongly peripheral to the potassic zone rather than in it. The concentration of iron sulfide in the alteration zone adjacent to the potassic is common to all deposits regardless of the type of alteration (phyllic, argillic, or propylitic) that may be peripheral to the potassic zone. The sulfide occurs dominantly as a dissemination in the altered rock. Size of the iron sulfide halo is variable.

Tourmaline can be found as an alteration mineral in several deposits (Earl, Quartz Creek, Vesper).

Mineralization: The distinctive feature in the economic mineralogy of porphyry copper deposits of the Cascades is the possibility that tungsten (as scheelite) may occur with copper and molybdenum sulfides north of the tungsten-molybdenum line.

Scheelite occasionally is found in other porphyry copper deposits (e.g., Gaspe). As wolframite, tungsten has also been reported from a number of deposits in Mexico. The persistence of scheelite in numerous Cascade porphyry copper deposits makes this group of deposits unusual. Tungsten is known in 8 of the 12 porphyry copper examples north of the tungsten-molybdenum line shown in Table 14. All these deposits have visible scheelite occurring mostly as a dissemination if in the potassic or phyllic zone or as a fracture filling if found in the zones peripheral to the phyllic. Wolframite has been reported from a few deposits but is not ordinarily identified. Whether this is because it habitually occurs in fairly fine easily bypassed crystals, or whether it simply is not a common constituent has not been determined.

The possibility that scheelite may occur in all alteration zones suggests it is highly mobile. If zinc and lead occur outside the porphyry deposit in a metallogenically zoned district, scheelite has been reported to occur in the zinc-lead veins as well. Since these veins most commonly occur in the propylitic alteration zone the appearance of scheelite there is not an anomaly in the Cascades.

Although tungsten has not yet been reported in Cascade porphyry deposits south of the tungsten-molybdenum line, molybdenum has been found in deposits in sporadic subeconomic amounts. The continued (though diminished) presence of molybdenum coupled with an almost complete absence of tungsten south of this line coincides with an apparent shift in composition of the ore-associated intrusion. South of the tungsten-molybdenum line quartz diorite is the only plutonic type known to be associated with ore sulfides. The change in composition of the pluton concomitant with disappearance of scheelite can be explained by either a change in the composition or in the thickness of the sialic crust.

In many respects Cascade porphyry copper examples are similar to the Tertiary diapiric or stock type deposits of the Canadian Cordillera. They may be separated into Babine Lake or inside types containing mineralization largely within the plutonic rocks (e.g., Middle Fork) or alternatively into those deposits whose ore minerals occur mostly in a biotite-rich contact zone adjacent to a boss or stock, the Berg or outside type exemplified by North Fork in the Cascades. In the latter, minor mineralization may also appear within the pluton as well. Since most deposits appear to contain sulfide in the intrusive as well as the intruded rock no genetic distinction is possible for the two types.

Ore sulfides in a biotite-rich potassic zone usually are disseminated within this zone. Ore sulfides within the phyllic zone most commonly are fracture controlled. Very little copper or molybdenum sulfide occurs outside the phyllic zone and all deposits explored to date have only a small developed tonnage.

Mineral zoning with zinc-lead-silver-gold values occurring in propylitically altered rocks adjacent to the copper zone typifies Cascade deposits. None of the zinc-lead deposits marginal to the porphyries has produced a significant tonnage of ore however.

Radiometric Age Relationships: Table 14 summaries radiometric dating for Cascade porphyry copper occurrences. In only a few cases have dates been determined for alteration silicates accompanying sulfide. The dates given are therefore largely for igneous rocks appearing to have a close time-space relationship to mineralization and mostly follow Armstrong, et al. (1976). No mineralized intrusions with Tertiary dates have been found east of the Pasayten fault and this fault may be considered the eastern boundary of this Tertiary province.

The Mazama deposit is located between a diorite porphyry and a quartz diorite porphyry in andesitic extrusives probably comagmatic with the former. The diorite has been dated at 84 m.y. and the quartz diorite at 70 m.y. (Wolfhard, 1976). Mineralization appears to be associated with the quartz diorite stock. The Monument stock has a 49 m.y. K-Ar date. Porphyry mineralization cuts this pluton but may approach it in age. A less clear association exists for the Ross Lake-Davis deposit. The nearby Chilliwack batholith has a 30 m.y. K-Ar age. If mineralization coincided with the dated phase of the Chilliwack batholith, the Ross Lake-Davis deposit is also 30 m.y. old. Vesper (also known as Sunrise or Bren-Mac) has been dated at 32 m.y. (Grant, 1976). Hydrothermal biotite with intergrown secondary quartz, plagioclase, and chalcopyrite has been found to have a 24 m.y. K-Ar date at McCoy Creek. This date appears to fix mineralization at that time. A clear case may be made for Glacier Peak as the Cloudy Pass pluton has been dated at 22 m.y. and the Glacier Peak ore deposit appears closely associated with it.

Quartz Creek, Middle Fork, and Mineral Creek deposits lie close to the Snoqualmie batholith, justifying speculative dating of these deposits at the same age as the pluton. With a K-Ar date of 18 m.y. the Snoqualmie batholith is one of the younger batholiths dated in the Cascades and the deposits near it may be assigned the same approximate dates.

The Earl deposit has a K-Ar date of 16.2 m.y. from hydrothermal biotite. A 21 m.y. date from magmatic biotite in the southern end of the Spirit Lake batholith about 10 miles south of the Earl is not considered to conflict with it.

North Fork near the Snoqualmie batholith has a K-Ar age of 9.9 m.y. from hydrothermal biotite. In both the North Fork and Earl datings the biotite was intergrown with chalcopyrite and therefore these dates are believed to represent ages of mineralization.

Hydrothermal sericite at Mesatchee provided a K-Ar date of 6.2 m.y.

The Cascade K-Ar dates 30, 24, 22, 18, 16, 9.9, and 6.2 m.y. agree with the geologic setting in each case. Apparent concordance between Cascade porphyry dates and Cascade volcanic rock suggest an episodic igneous history. Volcanic episodes at 0-2, 3-7, 9-11, and 14-18 m.y. have been recognized in central Oregon Cascade volcanic rocks and examples representative of each of these episodes exist in the Cascades porphyries. The 22 and 24 m.y. dates are nearly coincident with the Grotto (25.7 m.y.) and Monte Cristo (24.2 m.y.) stocks and early phases of the Tatoosh complex (Mattinson, 1973), suggesting another episode about 25 m.y. ago. The Earl (16.2 m.y.) date and dates for Snoqualmie and younger Tatoosh plutons are concordant with the 15-18 m.y. old Columbia volcanic episode. The 6.2 m.y. date for Mesatchee cannot be matched by other results from Washington but is similar to the 4-8 m.y. dates for the Laurel Hill stock. Mount Baker is a dormant volcano with a summit thermal-solfatara field that includes 78 000 sq m (9000 sq ft) of altered rock. Tephra associated with 1975 steam eruptions contains identifiable chalcopyrite as well as fairly common pyrite. The existence of chalcopyrite in this large currently developing alteration zone leads to speculation that a porphyry deposit is now forming within the Mount Baker thermal system.

No concensus has been reached on the question of whether or not subduction is active now or was a factor at the time the younger deposits formed in the Cascades.

Conclusions for Cascade Deposits

The Tertiary porphyry copper deposits west of the Pasayten fault have distinct alteration, mineralization, and age characteristics. They may include tungsten (scheelite) bearing phyllic and potassic zones. The deposits may contain pyrrhotite in place of or in addition to pyrite and may eventually be demonstrated to date as recently as the present. The deposits are typical stockwork or breccia structural types containing typical potassic zones and chalcopyrite and molybdenite are the most important ore minerals.

Known deposits appear to be located near or on one of several right lateral strike-slip faults. Movement of some of these faults may be speculated to be about 161-193 km (100-120 miles).

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