(2-02)
2290
76-51

Geologic interpretation of an aeromagnetic map of the west-central Columbia Plateau, Washington and Oregon

by

Donald A. Swanson, U.S. Geological Survey, Menlo Park, California 94025; Thomas L. Wright and Isidore Zietz, U.S. Geological Survey, Reston, Virginia 22092

Released: 1-76

Table of contents

Geologic interpretation of an aeromagnetic map of the west-central Columbia Plateau, Washington and Oregon

by

Donald A. Swanson, U.S. Geological Survey, Menlo Park, California 94025; Thomas L. Wright and Isidore Zietz, U.S. Geological Survey, Reston, Virginia 22092

Abstract

A low altitude, total intensity aeromagnetic map of the west-central Columbia Plateau, underlain principally by the Yakima Basalt, shows positive and negative anomalies that stand out from a moderate intensity background reflecting interbedded flows of normal and reversed magnetic polarity. One set of anomalies is related to anticlinal ridges, another follows the traces of known or inferred faults, and a third set coincides with a swarm of feeder dikes for the Ice Harbor flows of Swanson and others (1975b), the youngest unit of basalt in the area. A fourth set of narrow, sinuous anomalies is related to flows that filled ancient valleys during the late stage of Yakima volcanism. The magnetic map suggests that the Ice Harbor dike swarm is offset by left-lateral strike-slip displacement along the Rattlesnake-Wallula fault, a segment of the Olympic-Wallowa lineament. The aeromagnetic map is of great help in delineating the extent of the dike swarm, mapping the ancient drainage system, and understanding the structural history of this part of the Columbia Plateau.

Introduction

In 1957, a detailed total intensity aeromagnetic survey was made of a 27,000 km^2 area in south-central Washington and north-central Oregon (fig. 1). This area is in the west-central part of the Columbia

Figure 1 near here

Plateau, a large physiographic and geologic province underlain by the Miocene Columbia River Basalt Group, primarily the Yakima Basalt, and younger sedimentary rocks. The basalt is poorly exposed throughout much of the area, and the aeromagnetic data aid in locating and interpreting hidden structures, dikes, and ancient valleys filled with thick Yakima flows.

The aeromagnetic map (pl. 1) was compiled by J. R. Kirby and D. L.

Plate 1 near here

Daniels in 1970 from profiles obtained during north-south flights spaced about 1.6 km apart and 150 m above ground. The data are contoured in intervals of 100 gammas. This map is mostly consistent with, but much more detailed than, the high altitude (4600 m) aeromagnetic map of part of the same area published by Zietz and others (1971; specific examples of this consistency are described later in this paper.

We have interpreted the aeromagnetic data on the basis of reconnaissance field work by Swanson and Wright, supplemented by published geologic maps, especially that of Grolier and Bingham (1971). In addition, numerous papers and reports, some unpublished, were consulted. Detailed geologic maps are not available for much of the surveyed area, and some of the existing maps are inadequate because they predate recent advances in knowledge of the basalt stratigraphy. Consequently we cannot make a geologic evaluation of each aeromagnetic anomaly, although most of the major anomalies can be related to known or reasonably inferred geologic features. The tectonic map of Newcomb (1970), part of which is shown in modified form in figure 2, is the most complete

---

Figure 2 near here

---

structural compilation available and shows the general distribution of the basalt and younger sedimentary rocks. We are publishing this aeromagnetic map and our preliminary interpretation of it to encourage further study of the relation between geology and rock magnetism on the Columbia Plateau.

Geologic setting

The bedrock in the west-central part of the Columbia Plateau is the Yakima Basalt, the youngest formation in the Columbia River Basalt Group. The Yakima is a sequence of flood basalt flows mostly erupted during a 3 m.y. period centered about 15 m.y. ago (Watkins and Baksi, 1974), although eruptions continued intermittently until between 8 and 9 m.y. ago (unpublished K/Ar ages by E. H. McKee). The basalt has been subdivided into several units, summarized in figure 3. The maximum

---

Figure 3 near here

---

thickness of Yakima Basalt in this area is at least 600 m (Diery and McKee, 1969) and may be several times that. An oil-test hole on the Rattlesnake Hills about 60 km west-northwest of Pasco penetrated 3,248 m of basalt and andesite (?) without encountering basement (Raymond and Tillson, 1968), but at least the lower 1800 m of the basalt and andesite (?) may be of early Miocene age or older (Newman, 1970) and therefore older than the Yakima Basalt. The basalt was presumably erupted from north-northwest trending fissures, those for the Ice Harbor flows of Swanson and others (1975b; fig. 3) being located in the southeast corner of the map area.

Thin sedimentary deposits of small lateral extent occur between some of the basalt flows, especially near the top of the Yakima section. These deposits consist largely of fresh andesitic debris newly erupted from volcanoes in the Cascade Mountains but include some epiclastic material derived from sources on and surrounding the plateau. Similar deposits overlie the basalt in valleys near Yakima. Pliocene and Pleistocene basalt and andesite flows erupted farther west occur locally along the west edge of the map area.

Younger sedimentary deposits blanket areas along and east of the Columbia River. These deposits, from Pliocene to late Pleistocene in age, consist of a mixture of reworked andesitic debris and epiclastic material derived from the plateau and the surrounding mountainous regions. Some of these deposits date from the Spokane floods (Bretz and others, 1956; Baker, 1973), others contain Pleistocene lake sediments, and still others represent Columbia River sands and gravels. A thin mantle of loess occurs in places. The thickest section of sedimentary deposits occupies the structurally and topographically lowest basin in the area, the Pasco Basin, where fluvial and lake beds more than 230 m thick have been cored (Brown and Ledgerwood, 1973).

The regional dip of the basalt in the area is toward the Pasco Basin, ~~probably~~ averaging less than 15 m/km. This regional dip is broken in several places by sharp anticlines and synclines, which form linear topographic ridges and valleys (figs. 1 and 2). Most of these folds trend west-southwest to west-northwest, but they are oriented northwest in a zone extending diagonally across the center of the area and passing through Ellensburg and Pasco. Some of the anticlines and synclines may have begun to form in late Yakima time (Waters, 1955; Schmincke, 1967a), but most owe their present elevation to subsequent folding.

The Columbia Plateau lies on the continental side of an andesitic chain, the Cascade Mountains, and was an area of extension along north-northwest fissures during a time of contemporaneous Cascade volcanism. Many of the extensional fissures cut crustal rocks from Precambrian to Mesozoic in age, but new crust may have been generated beneath the Pasco Basin in the form of a large swarm of dikes or a mantle diapir (Hill, 1972). Thus the plateau bears some resemblance to a marginal basin (Karig, 1971), with due allowance for continental interaction.

Interpretation

In most places, the Yakima Basalt consists of gently dipping, areally extensive lava flows with both normal and reversed magnetic polarities. The normal and reversed flows are interbedded (fig. 3). Consequently the expected aeromagnetic pattern should be rather featureless and of low magnetic intensity despite the highly magnetized character of single flows. This type of pattern typifies much of the map, where intensities range from 500-900 gammas and anomalies are of small amplitude and extent. Beneath such areas, the likelihood of complicated structure or intense diking is minimal, at least at shallow depth. Thus one can attempt correlations across these areas without much concern about structural complexity, even though the basalt may be poorly exposed or even concealed.

Numerous linear anomalies of moderate to large amplitude stand out above the featureless background. These anomalies must have causes other than flat-lying extensive flows. Our analysis suggests that some of these linear anomalies reflect topography (most of which is structurally controlled) and others are related to known dikes and lava-filled paleovalleys. A few irregularly shaped anomalies record the presence of features as yet unidentified by other means.

Anomalies related to structurally-controlled topography

The Yakima Basalt is uplifted and folded along several long, narrow, anticlinal and monoclinal ridges in the area (Waters, 1955; Newcomb, 1970). Many of the anticlines are asymmetric, generally with a steeper north limb forming an abrupt scarp. The aeromagnetic anomalies reflect these anticlinal ridges and their asymmetry. Examples are the Horse Heaven Hills between 119° and 120° W. longitude (~~number~~ anomaly 1, pl. 1), the Rattlesnake Hills-Red Mountain-Badger Mountain chain of ridges west of Pasco (2), Toppenish Ridge (3), Yakima Ridge (4), parts of Gable Mountain and Gable Butte on the Hanford Reservation (5), Saddle Mountains (6), to a poor degree the Frenchman Hills (7), and the Alder Ridge-Golgotha Butte area northeast of Arlington, Oregon (8). These anomalies are presumably related to flows that dip away from the eroded ridgecrest; as a result of the dip and the erosion, flow sequences of uniform magnetic polarity are exposed rather than hidden in the "sandwich" of normal and reversed flows that characterizes areas between ridges.

The anomalies are paired along some of the steepest north-facing scarps, a positive anomaly occurring near the top of the scarp and a negative anomaly toward the base; good examples are anomalies 1 and 2. This may largely result from the fact that the earth's magnetic field is not vertical in this area (Nettleton, 1971). Changing flight altitude is probably not a major contributing factor to the anomaly pattern, as a nearly constant altitude above ground was supposedly maintained.

Another type of topography-related anomaly is the sinuous magnetic high (9) that approximately coincides with the north bank of the Columbia River upstream from McNary Dam, 30 km southwest of Pasco. Here, bold cliffs exposing nearly horizontal flows of normally polarized basalt, chiefly Frenchman Springs Member, were produced during the late Pleistocene floods that drained Lake Missoula (Bretz and others, 1956; Baker, 1973) and stripped away unconsolidated sedimentary deposits overlying the basalt. The positive magnetic anomaly may reflect these bare cliffs.

Anomalies related to dikes

The cluster of four N20°-30°W-trending positive and negative anomalies (10-13) in the southeast part of the area crosses nearly flat, featureless terrain. Single anomalies within this cluster are as much as 80 km long, less than 4 km (generally less than 2 km) wide, and have amplitudes of 400-500 gammas above the regional background. The anomalies are remarkably straight, continuous, symmetric, and show no change in character as they pass from areas of basalt outcrop into areas where the basalt is covered by thin sedimentary deposits. The anomalies are probably shallow features, as suggested by their high gradient, narrow width, and absence from the high altitude aeromagnetic map of Zietz and others (1971, fig. 1).

We interpret these anomalies to be caused by a system of mostly concealed dikes known from geologic mapping to occur in the area (Swanson and others, 1972; Swanson and others, 1975b; Helz and others, in press). These dikes fed the Ice Harbor flows, which are 8-9 m.y. old (unpublished K/A ages by E. H. McKee) and constitute the youngest flows of Yakima Basalt within the area of the aeromagnetic map. The Ice Harbor flows have been subdivided by Helz and others (in press) and Swanson and others (1975b) into four subunits, from oldest to youngest with paleomagnetic polarity in parantheses, Basin City (normal), Ice Harbor 1 (reversed), upper Ice Harbor 1 (reversed?), and Ice Harbor 2 (normal). The paleomagnetic polarities were determined in the field with a portable fluxgate magnetometer.

Swanson and others (1975b) described 18 vent and near-vent areas for these four units and showed how they were aligned into linear vent systems coincident with the aeromagnetic anomalies. The northern third of the Basin City vent system follows a narrow, shallow graben (Swanson and others, 1975b, p. 894). The Ice Harbor 1 vent system occurs along the western negative anomaly (11), the upper Ice Harbor 1 system along the eastern negative anomaly (13), and the Basin City and Ice Harbor 2 systems along the intervening positive anomaly (12). Two vent areas for Ice Harbor 2 deviate from this general pattern and suggest a right offset en echelon fissure set not reflected by the magnetics (Swanson and others, 1975b, p. 894-895). No dikes have been found for the broad westernmost positive anomaly (10), but this area is completely covered with young sedimentary deposits. In fact, the entire area underlain by the Ice Harbor flows is poorly exposed, and the aeromagnetic data provide a far more complete picture of the dike swarm than does the field mapping alone.

The observed dikes are all vertical, thin (less than 3 m wide), and trend parallel to the anomalies. It seems unlikely, however, that one such dike could itself be responsible for the size and amplitude of a particular anomaly. More likely, a set of several closely spaced dikes of uniform polarity, or a single wide dikelike body, underlies each anomaly. For example, two dikes and one thin dikelet occur on the north bank of Snake River where it crosses anomaly 12.

The anomalies do not strictly parallel each other but instead trend progressively more northerly from east to west. Such a change in azimuth could be related to slight tectonic rotation, if it could be demonstrated that the age of the dikes changes systematically across the swarm. This is not the case, however, as the oldest dikes (Basin City) are sandwiched between dikes of younger age. Apparently the divergent trends are related to something other than rotation.

Several other narrow, northwest-trending anomalies may be related to dikes, although no dikes have been found associated with them. Examples are the set of negative anomalies (14) that crosses the Snake River near the border of T. 10 and 11 N., R. 33 E., near the railroad siding called Snake River; the anomalies (15) in and adjacent to T. 15 and 16 N., R. 31 E. west of Cunningham; and the general northwest grain (16) in T. 14 and 15 N., R. 33 E. southeast of Cunningham. These anomalies all have lower amplitudes than those of the Ice Harbor dike swarm and may reflect smaller or more deeply buried dike systems.

One thick dike and two thin ones, feeders for a normally polarized flow in the Frenchman Springs Member, are located on both sides of the Snake River in sec. 1, T. 11 N., R. 33 E, 10 km northeast of the railroad siding, Snake River (Swanson and others, 1975b, pl. 1 B). These dikes, which trend N 25° W, have little magnetic expression, suggesting that they do not greatly widen or become more numerous within the depth range affecting the magnetometer.

Anomalies related to faults

The anomalies related to the Ice Harbor dikes appear to terminate south of the Walla Walla River against a zone of west-northwest trending, positive and negative anomalies that form the southeast continuation of the Rattlesnake Hills-Red Mountain-Badger Mountain trend. The pattern of termination suggests strike-slip offset along a fault or fault zone that extends at least as far northwest as the Columbia River, and probably farther northwest along the Rattlesnake Hills-Badger Mountain trend. One of the west-northwest trending, negative anomalies (17) is associated with a fault mapped by Newcomb (1965) that defines the southwest margin of the Walla Walla Basin; further northwest, this anomaly coincides with the Rattlesnake-Wallula fault of Bingham and others (1970). This anomaly may partly reflect the topography along the eastern extension of the Horse Heaven Hills, but the basic fault control is suggested by its relation to the dikes. Other anomalies south of the Walla Walla Basin follow the linear valleys of Vansycle Canyon, Warm Springs Canyon, and the valley east of Warm Springs Canyon, mapped as faults or fracture zones by Newcomb (1965), Bingham and others (1970), and Walker (1973). Thus both geologic and geophysical evidence supports the existence of a fault zone in the area of truncated, dike-related anomalies.

The sense of displacement along the fault zone cannot be demonstrated, though left-lateral offset is suggested if the assumption is made that the dike-related anomalies are offset by the fault zone. No such anomalies occur on the south side of the fault zone west of Wallula Gap, as they would if they had been offset by right-lateral displacement. Magnetic coverage in this area is reasonably good and would be expected to reveal the anomalies if present. Coverage along the southeast continuation of the fault zone is incomplete; if future aeromagnetic surveys of this area (scheduled for the fall of 1975) reveal dike-related anomalies, the left-lateral sense of displacement will be a strong possibility.

The Rattlesnake-Wallula fault zone forms part of the Olympic-Wallowa lineament, as defined by Raisz (1945) on the basis of topography and discussed by many workers, especially Wise (1963), Skehan (1965), Watkins (1965; 1967), and Taubeneck (1966; 1967). Whether this topographic lineament has regional tectonic significance is debatable, but available evidence now favors the Rattlesnake Hills-Walla Walla Basin segment of the lineament being at least partly fault controlled.

Other anomalies on the map may be associated with faults and shear zones. For example, the strong west-northwest grain in the extreme southwest part of the map has the same trend as faults that occur a few kilometres farther west and south (Newcomb, 1970; fig. 2) and may reflect similar structures. These anomalies cross shallow east-trending folds in this area, such as the Swale Creek-Glade Creek syncline (Newcomb, 1970), with no deflection. The anomalies also appear to transect the large fold associated with the Horse Heaven Hills in T. 6 N., R. 19 E., 18 km east-northeast of Satus Pass.

Anomalies along the Rattlesnake Hills-Badger Mountain trend and the southeast-trending part of the Horse Heaven Hills may well be related to faults as well as topographic expression. Bingham and others (1970) mapped three faults in these areas, and two of these, the Rattlesnake-Wallula and Wallula Gap faults, are known to have associated magnetic anomalies, as seen on plate 1 and from unpublished data.

Anomalies associated with valley-filling basalt flows

Ancient valleys filled with basalt flows occur on the Columbia Plateau (Lupher and Warren, 1942). These valleys were cut and filled during the waning stage of Yakima volcanism (Swanson and others, 1975). All known paleovalleys within the map area are reflected by magnetic anomalies; this relation can be used to infer the course of these valleys beneath concealed areas. The anomalies are thought to reflect the filling of narrow valleys by a flow so thick that its magnetic intensity is much stronger than that of wallrock, which consists of interbedded flows of reversed and normal polarity that tend to cancel each other.

The two narrow, sinuous anomalies (18 and 19) trending east-west between Esquatzel Coulee and the Snake River occur in a very poorly exposed area between localities of mapped intracanyon flows. Remnants of intracanyon flows belonging to the Pomona and Elephant Mountain Basalt Members of Schmincke (1967b) occur wherever exposures can be found along these anomalies, such as in Old Maid and Esquatzel Coulees. A particularly good exposure of an Elephant Mountain flow filling a valley is at Cactus Siding in Esquatzel Coulee (Grolier, 1965, p. 107-108). The two anomalies converge eastward and appear to connect with mapped remnants of valley-filling Pomona and Elephant Mountain flows in Wilson Canyon, 3 km west of Devils Canyon. These and other valley-filling flows can be traced in the field eastward from Wilson Canyon for many tens of kilometres; they define the location of the ancestral Snake River during late Miocene time.

The flow of the Pomona Basalt Member is the only intracanyon flow known to occur along the southernmost (18) of the two anomalies, and its reversed polarity (Rietman, 1966) probably accounts for the negative anomaly. The Elephant Mountain Basalt Member is the only known intracanyon flow along the northernmost anomaly (19). Its polarity is weakly normal to transitional (Rietman, 1966), a state especially susceptible to acquiring an unstable, relatively strong "pseudo-normal polarity" in the earth's present magnetic field (Watkins and Baksi, 1974, p. 157). Such a "pseudo-normal polarity" may account for the positive anomaly. There is a suggestion from anomaly 19 that a reversely polarized flow (Pomona?) may also be present.

Were it not for the aeromagnetic data, we would be unable to trace the ancient valleys between Esquatzel Coulee and Wilson Canyon, and thus these data are of much importance in determining the late Miocene paleography of the area.

Using this example as a guide, we suggest that several other narrow, sinuous anomalies on the map reflect ancient lava-filled valleys. One such example about 5 km northwest of Othello is especially clear. Here, an unnamed flow, recognized as filling a valley by Grolier (1965, p. 106-107) and mapped by Grolier and Bingham (1971), coincides with a gently curving, narrow, southwest-trending positive magnetic anomaly (20). The magnetic polarity of the flow, as determined in the field with a portable fluxgate magnetometer, is also normal. This anomaly can be traced with confidence northeastward to a point about 8 km southwest of Warden, where it apparently swings eastward and continues south of Lind Coulee for 13 km; the mapped intravalley flow swings eastward with the anomaly, before disappearing beneath younger sedimentary deposits (Grolier and Bingham, 1971). Southwest from the Othello area, the anomaly apparently continues across the Saddle Mountains as far as the Columbia River and may extend up the Columbia at least as far west as long. 120° W. If these correlations are correct, the aeromagnetic data trace the ancient valley and its basalt filling for a distance of 80 km, along most of which no outcrops were found by Grolier and Bingham (1971) because of younger deposits.

A faint, east-trending negative anomaly (21) about 3 km northeast of Beverly, a village on the Columbia River just north of Saddle Mountains, may correspond to the Jericho flow tongue of Grolier (1965, p. 108), which he interpreted to be a valley-filling flow. The narrow, east-trending positive anomaly (22) extending from the westernmost dike anomaly toward Richland may record a valley filled with a flow erupted from the dike.

Numerous other narrow, sinuous magnetic anomalies on the map are not associated with obvious topography or structure and should be considered as possible indicators of old valleys filled with younger basalt flows.

Major anomalies of unknown origin

Several large anomalies have no obvious cause. The most striking is the broad positive anomaly (23) in the area immediately southeast of Cunningham. This anomaly also shows up on the high altitude magnetic map of Zietz and others (1971, fig. 1). The basalt in this area is poorly exposed, being mantled except in some valleys by tuffaceous sedimentary deposits and loess (Grolier and Bingham, 1971). A generalized water-level contour map of this area (Luzier and Burt, 1974, pl. 2) shows an area of unusually shallow water depth updip (northeast) from the area of the magnetic anomaly. This suggests that the anomaly may reflect a structure or rock body that serves as a ground-water barrier. Three possible sources of the anomaly consistent with its appearance on both magnetic maps are a shallow mafic intrusive body, a basement high, or a structural dome. Interestingly, the largest ground-water barrier that

Luzier and Burt (1974, p. 11-14) found, between Ruff and Lind in the northeast part of plate 1, has no strong magnetic expression, although the general magnetic trend in this area parallels the northwest-trending barrier.

Another unexplained feature is the broad positive anomaly (24) south of Richland. This could result from a thick Ice Harbor flow ponded against the ancestral Rattlesnake-Wallula structure. Alternatively, the anomaly could reflect a deeper feature, such as a buried basement high, particularly since the high altitude aeromagnetic map of Zietz and others (1971, fig. 1) shows a broad positive anomaly that includes the Richland area.

A nearly circular positive anomaly (25) along the northeast margin of Kittitas Valley near Ellensburg is also puzzling. The anomaly is centered over alluvium within 10 km of the margin of the basalt field (Newcomb, 1970). Its shape suggests a buried prebasalt hill or a shallow pluton of post-Yakima age.

Three broad negative anomalies are of unknown origin. Anomaly 26, in the Quincy Basin north of the Frenchman Hills, is developed over Quaternary fluvial and lacustrine sand and silt (Grolier and Bingham, 1971) and may reflect a thick deposit of these weakly magnetized materials. Anomaly 27, west of Jackass Mountain, may have a similar origin, as this area is also underlain by lacustrine clay, silt, and fine sand of Quaternary age (Grolier and Bingham, 1971). Anomaly 28, a lobate anomaly on the Royal Slope and in the western part of the Drumheller Channels, is developed over both basalt flows and Quaternary sedimentary deposits (Grolier and Bingham, 1971) and may have a composite origin. Many of the exposed flows in this area are reversely polarized (Priest Rapids Member, Pomona Basalt Member of Schmincke [1967b]) and would contribute to a negative anomaly, together with the sedimentary deposits. However, it is also possible that deeper-seated structures are the source of these three anomalies, as the high altitude aeromagnetic map (Zietz and others, 1971) shows prominent magnetic lows coinciding with anomalies 27 and 28 and the southern part of anomaly 26.

There is one intriguing difference between the high altitude and low altitude magnetic maps. The high altitude map (Zietz and others, 1971, fig. 1) shows a striking linear set of anomalies trending northwest located along or somewhat south of the eastern half of the Horse Heaven Hills anticline (pl. 1, anomaly 1). This high altitude anomaly extends at least 20 km farther northwest than the low altitude anomaly and may reflect a deeper part of the structure than can be seen using the low altitude data.

Relation between aeromagnetic and gravity anomalies

Correspondence between aeromagnetic and Bouguer gravity (Bonini and others, 1974; Koniček, 1974) anomalies is poor in south-central Washington. The gravity data are most likely influenced by deeper structures and rock bodies than are the low-altitude aeromagnetic data. One possible exception is the spatial correspondence between the aeromagnetic anomaly along the Rattlesnake Hills west of Pasco (pl. 1, anomaly 2) and a northwest-trending gravity gradient that defines the northeast side of a positive anomaly centered near lat. 46°15'N, long. 119°40'W. Perhaps the aeromagnetic anomaly and gravity gradient are both related to a structure along the Olympic-Wallowa lineament. South of Pasco, however, the aeromagnetic and gravity trends in the area of the lineament are markedly discordant.

Conclusions

The low altitude aeromagnetic map corresponds closely to the known geology and enables extrapolations to be made across poorly exposed areas. It outlines the limits of the Ice Harbor dike system better than would ever be possible from knowledge of the surface geology alone. The anomaly patterns suggest the first evidence of strike-slip displacement along the Rattlesnake-Wallula fault. The magnetic map also greatly aids in reconstructing the drainage system that formed during the late state of Yakima volcanism. The map suggests areas that should be examined more closely in the field and significantly contributes to an understanding of the late Cenozoic history of the area. Aeromagnetic coverage of the entire Columbia Plateau, especially along the southeast extension of the Rattlesnake-Wallula fault, would be invaluable toward this end.

Acknowledgements

We thank J. R. Kirby and D. L. Daniels for compiling the aeromagnetic data; A. J. Froelich, M. W. Higgins, M. J. Grolier, and R. T. Helz for beneficial reviews; Helz for considerable help in studying the Ice Harbor dikes; and B. A. Siems for pointing out the paper by Luzier and Burt (1974).

References cited

Baker, V. R., 1973, Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington: Geol. Soc. America Spec. Paper 144, 79 p.

Bingham, J. W., Londquist, C. J., and Baltz, E. H., 1970, Geologic investigation of faulting in the Hanford region, Washington: U.S. Geol. Survey open-file rept., 104 p.

Bonini, W. E., Hughes, D. W., and Daneš, Z. F., 1974, Complete Bouguer gravity anomaly map of Washington: Washington State Div. Geol. and Earth Resources, Geol. Map GM-11, scale 1:500,000.

Bretz, J. H., Smith, H.T.U., and Neff, G. E., 1956, Channeled scablands of Washington: New data and interpretations: Geol. Soc. America Bull., v. 67, p. 957-1049.

Brown, D. J., and Ledgerwood, R. K., 1973, Stratigraphy and structure of Yakima Basalt in the Pasco Basin, Washington: Oregon Dept. Geol. Miner. Indus. Bull. 77, p. 171-181.

Diery, H. D., and McKee, Bates, 1969, Stratigraphy of the Yakima Basalt in the type area: Northwest Sci., v. 143, p. 47-64.

Grolier, M. J., 1965, Geology of part of the Big Bend area, in the Columbia Plateau, Washington: Ph.D. Diss., Johns Hopkins University, Baltimore, 267 p.

Grolier, M. J., and Bingham, J. W., 1971, Geologic map and sections of parts of Grant, Adams, and Franklin Counties, Washington: U.S. Geol. Survey Misc. Geol. Inv. Map I-589, scale 1:62,500.

Helz, R. T., Wright, T. L., and Swanson, D. A., in press, Petrogenetic significance of chemical trends in the youngest unit of Yakima Basalt on the Columbia Plateau, northwest U.S.A.: Bull. Volcanologique.

Hill, D. P., 1972, Crustal and upper mantle structure of the Columbia Plateau from long range seismic-refraction measurements: Geol. Soc. America Bull. v. 83, p. 1639-1648.

Holmgren, D. A., 1970, K/Ar dates and paleomagnetics of the type Yakima Basalt, central Washington: p. 189-199 in Proc. Second Columbia River Basalt Symposium, E. H. Gilmour and Dale Stradling, eds., Eastern Washington State Coll. Press, Cheney, 33 p.

Karig, D. E., 1971, Origin and development of marginal basins in the western Pacific: Jour. Geophys. Research, v. 76, p. 2542-2561.

Koníček, D. L., 1974, Geophysical survey in south-central Washington: M. S. Thesis, University Puget Sound, Tacoma, Washington, 35 p.

Lupher, R. L., and Warren, W. C., 1942, The Asotin stage of the Snake River Canyon near Lewiston, Idaho: Jour. Geol., v. 50, p. 866-881.

Luzier, J. E., and Burt, R. J., 1974, Hydrology of basalt aquifers and depletion of ground water in east-central Washington: Wash. State Dept. Ecology Water-Supply Bull. 33, 53 p.

Nettleton, L. L., 1971, Elementary gravity and magnetics for geologists and seismologists: Soc. Exploration Geophys., Mono. 1, 121 p.

Newcomb, R. C., 1965, Geology and ground-water resources of the Walla Walla River Basin, Washington-Oregon: Washington Div. Water Resources, Water Supply Bull. 21, 151 p.

Newcomb, R. C., 1970, Tectonic structure of the main part of the basalt of the Columbia River Group, Washington, Oregon, and Idaho: U.S. Geol. Survey Misc. Geol. Inv. Map I-587, Scale 1:500,000.

Newman, K. R., 1970, Palynology of interflow sediments from the Standard Oil Company of California Rattlesnake Hills No. 1 well, Benton County, Washington: p. 201-207, in Proc. Second Columbia River Basalt Symp., E. H. Gilmour and Dale Stradling, eds., Eastern Washington State College Press, Cheney, 33 p.

Raisz, Erwin, 1945, The Olympic-Wallowa lineament: Am. Jour. Sci., v. 243A, p. 479-485.

Raymond, J. R., and Tillson, D. D., 1968, Evaluation of a thick basalt sequence in south central Washington: AEC Research and Development Report, BNWL-776, 126 p.

Rietman, Jan, 1966, Remanent magnetization of the late Yakima Basalt, Washington State: Ph.D. Diss., Stanford University, Stanford, California, 87 p.

Schmincke, H.-U., 1967a, Flow directions in Columbia River basalt flows and paleocurrents of interbedded sedimentary rocks, south-central Washington: Geol. Rundschau, v. 56, p. 992-1020.

______1967b, Stratigraphy and petrography of four upper Yakima basalt flows in south-central Washington: Geol. Soc. America Bull., v. 78, p. 1385-1422.

Skehan, J. W., 1965, A continental-oceanic crustal boundary in the Pacific Northwest: Air Force Cambridge Research Lab., Scientific Rept. 3, AFCRL-65-904, 52 p.

Swanson, D. A., and Wright, T. L., 1976, Magnetostratigraphic units in the Yakima Basalt, southeast Washington: Geol. Soc. America Absts. with Programs, v. 8.

Swanson, D. A., Wright, T. L., and Clem, Richard, 1975a, Intracanyon flows of Yakima Basalt along the Snake River, southeast Washington: Geol. Soc. America Absts. with Programs, v. 7, no. 5, p. 645.

Swanson, D. A., Wright, T. L., and Helz, R. T., 1975b, Linear vent systems and estimated rates of magma production and eruption for the Yakima Basalt on the Columbia Plateau: Am. Jour. Sci., v. 275, p. 877-905.

Swanson, D. A., Wright, T. L., Grolier, M. J., Higgins, M. W., and Zietz, Isidore, 1972, Feeder dikes for Yakima Basalt near Pasco, Washington: Geol. Soc. America Absts. with Programs, v. 4, no. 3, p. 245.

Taubeneck, W. H., 1966, An evaluation of tectonic rotation in the Pacific Northwest: Jour. Geophys. Res., v. 71, p. 2113-2120.

_____1967, Reply: Jour. Geophys. Res., v. 72, p. 1415-1421.

Walker, G. W., 1973, Reconnaissance geologic map of the Pendleton quadrangle, Oregon and Washington: U.S. Geol. Survey Misc. Geol. Inv. Map I-727, scale 1:250,000.

Waters, A. C., 1955, Geomorphology of south-central Washington, illustrated by the Yakima East quadrangle: Geol. Soc. America Bull., v. 66, p. 663-684.

_____1961, Stratigraphic and lithologic variations in the Columbia River basalt: Am. Jour. Sci., v. 259, p. 583-611.

Watkins, N. D., 1965, Paleomagnetism of the Columbia plateaus: Jour. Geophys. Res., v. 70, p. 3179-1406.

_____1967, Comments on a paper by William H. Taubeneck, 'An evaluation of tectonic rotation in the Pacific Northwest': Jour. Geophys. Research, v. 72, p. 1411-1414.

Watkins, N. D., and Baksi, A. K., 1974, Magnetostratigraphy and oroclinal folding of the Columbia River, Steens, and Owyhee basalts in Oregon, Washington, and Idaho: Am. Jour. Sci., v. 274, p. 148-189.

Wise, D. U., 1963, An outrageous hypothesis for the tectonic pattern of the North American Cordillera: Geol. Soc. America Bull., v. 74, p. 357-362.

Wright, T. L., Grolier, M. J., and Swanson, D. A., 1973, Chemical variation related to the stratigraphy of the Columbia River basalt: Geol. Soc. America Bull., v. 84, p. 371-386.

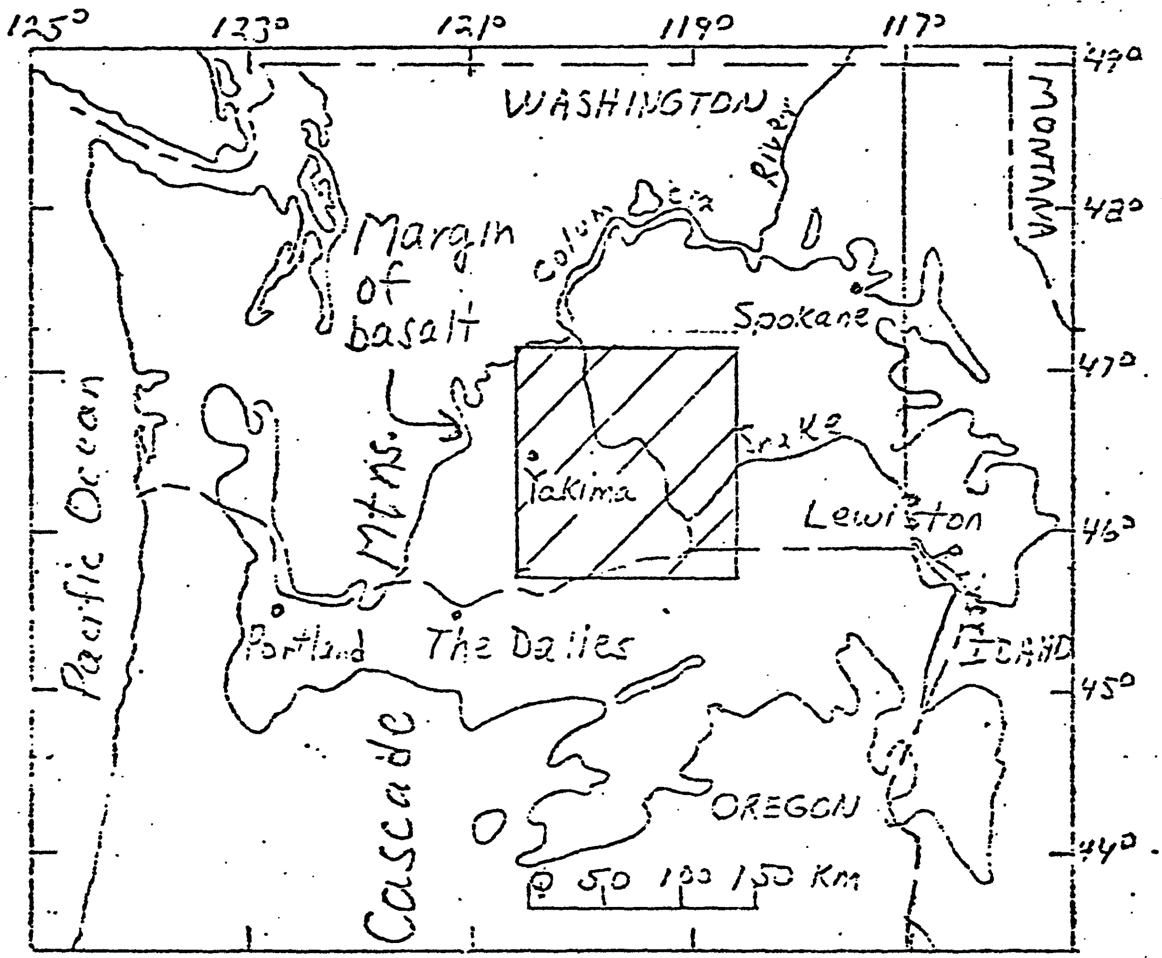
Zietz, Isidore, Hearn, B. C., Higgins, M. W., Robinson, G. D., and Swanson, D. A., 1971, Interpretation of an aeromagnetic strip across the northwestern United States: Geol. Soc. America., v. 82, p. 3347-3372.

Figure captions

Figure 1. Index map showing location of aeromagnetic survey and approximate extent of the Columbia River Basalt Group. The Columbia Plateau is a loosely defined term for the area east of the Cascade Mountains underlain by the Columbia River Basalt. The extent of the basalt is after Waters (1961).

Figure 2. Structural map of west-central Columbia Plateau, simplified and slightly modified from Newcomb (1970). The most important structures have topographic expression, as shown by comparison with the base to the aeromagnetic map. The Rattlesnake-Wallula fault of Bingham and others (1970) lies just northeast of the line of short anticlinal axes a few kilometres southwest of Pasco.

Figure 3. Summary of stratigraphic nomenclature for the principal units of Yakima Basalt in the west-central Columbia Plateau. Magnetic polarity, shown as normal (N), transitional (T), or reversed (R), are from Rietman (1966), Helz and others (in press), and Swanson and Wright (1976). Potassium-argon ages for the upper Yakima basalt are from E. H. McKee (written commn., 1975). Older flows are mostly 16-13 m.y. old (Watkins and Baksi, 1974; Holmgren, 1970).



125°
123°
121°
119°
117°
49°
48°
47°
46°
45°
44°
WASHINGTON
MONTANA
River
Columbia
Margin
of
basalt
Spokane
Snake
Yakima
Lewiston
Pacific Ocean
Mtns.
Cascade
Portland
The Dalles
IDAHO
OREGON
0 50 100 150 Km

Figure 1

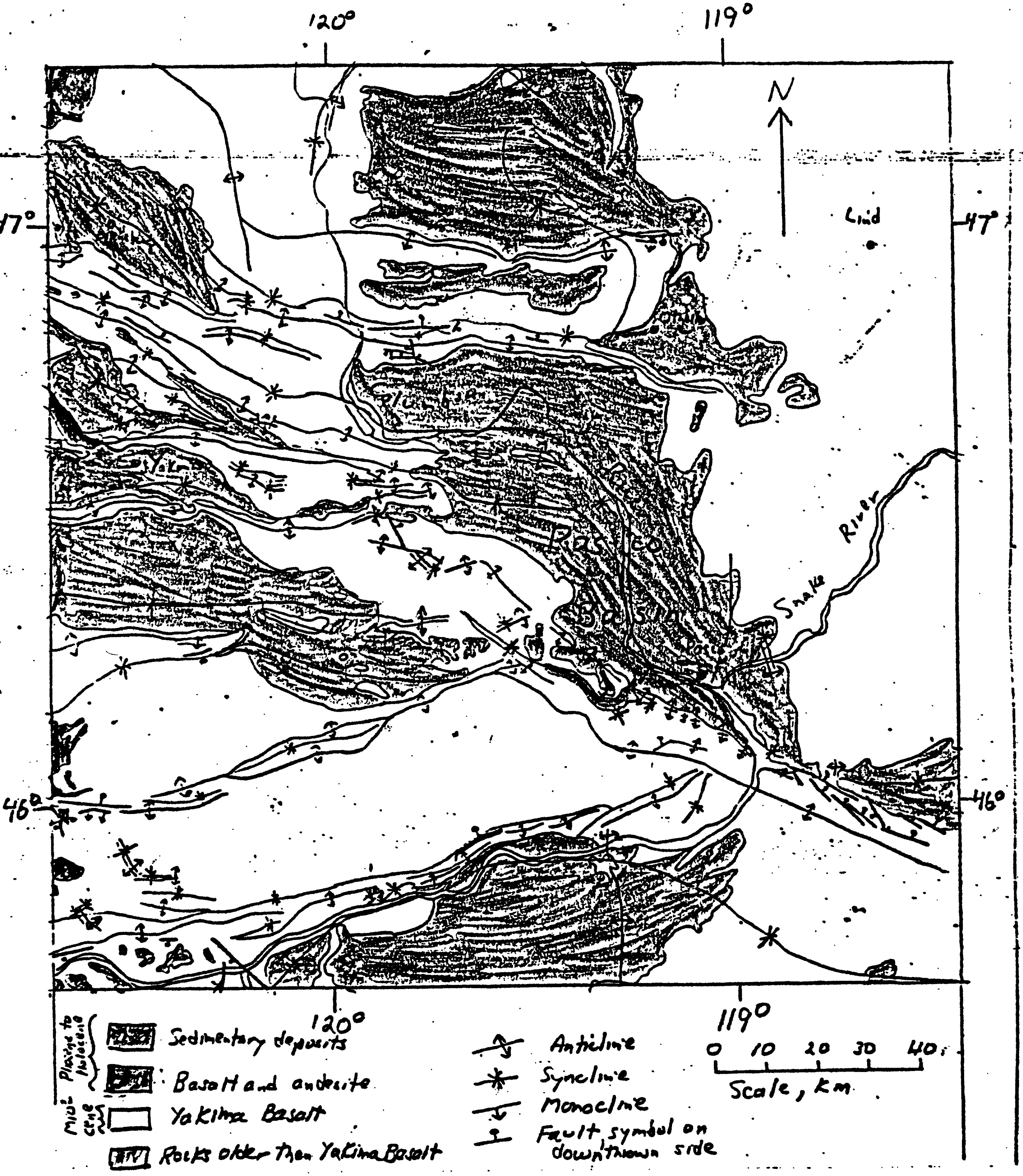

120°
119°
47°
46°
N
Lind
Pasco Basin
Pasco
Snake River
Sedimentary deposits
Basalt and andesite
Yakima Basalt
Rocks older than Yakima Basalt
Anticline
Syncline
Monocline
Fault symbol on downthrown side
0 10 20 30 40
Scale, km

Fig. 2

				Ages, m.y.
Upper Yakima basalt of Wright and others (1973)	Ice Harbor flows of Swanson and others (1975b)	Ice Harbor 2	N	8-9
		Upper Ice Harbor 1	R	
		Ice Harbor 1		
		Basin City	N	
	Elephant Mountain Basalt Member of Schmincke (1967b)			10-11
	Pomona Basalt Member of Schmincke (1967b)		R	11-13
Middle Yakima basalt of Wright and others (1973)	Priest Rapids Member	Umatilla Basalt Member of Schmincke (1967b)	N?	
		Unnamed flows	R	
	Roza Member		T	
	Frenchman Springs Member		N	
Lower Yakima basalt of Wright and others (1973)	Mostly unnamed flows		R	
			N	
			R	

Figure 3