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REPORT ON THE GEOLOGY AND GENESIS OF THE YERINGTON PORPHYRY COPPER DISTRICT, NEVADA, A FOUR DIMENSIONAL STUDY, AS SUPPORTED BY USGS MINERAL RESOURCE EXTERNAL RESEARCH PROGRAM GRANT 06HQGR0171

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REPORT ON THE GEOLOGY AND GENESIS OF THE YERINGTON PORPHYRY COPPER DISTRICT, NEVADA, A FOUR DIMENSIONAL STUDY, AS SUPPORTED BY USGS MINERAL RESOURCE EXTERNAL RESEARCH PROGRAM GRANT 06HQGR0171

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1. INTRODUCTION

The principal investigator applied for a US Geological Survey external grant in February, 2006 in order to further our geologic understanding of the Yerington, Nevada, porphyry copper district. A basic understanding of the geology of this district has been developed over a period of more than 40 years through geologic work there by the principal investigator and others. USGS MRERP Grant 06HQGR0171 was approved for an amount of $40,000, about 58 percent of the original proposed budget, for the period August 4, 2006 to June 30, 2007. These funds have allowed a high proportion of the specific goals outlined in the original proposal to be achieved. The original proposal was for the period September 30, 2006 to September 29, 2007, in order to allow for prior commitments of the principal investigator (related to the Alaska field season). The June 30, 2007 end date for the grant, combined with a delay in receipt of funds until the end of December, 2006, restricted much of the work to the January - June, 2007 period. As a result, some aspects of the work, such as plotting and interpretation of some of the new field mapping, final chemical analyses on some of the rock samples, and some of the petrography are still in progress (at the expense of the principal investigator). Work still in progress, as well as that reported below, are also in preparation for submittal for publicaition.

The Yerington district contains four known porphyry copper deposits, all related to porphyries in the upper part of the Jurassic age Yerington batholith. Much of what is know about porphyry copper deposits from work in other districts is based on rocks and ores exposed within and adjacent to the deposits, with limited information about underlying rocks, or about rocks that originally were above the deposits. Therefore many ideas about deeper-seated phenomena that result in formation of these deposits, or about relationships of deposits to volcanism and near-surface hydrothermal activity, must be based largely on inference and speculation. In the Yerington district late Cenozoic extensional faulting and tilting (Proffett, 1977) has exposed rocks in several fault blocks that were originally cross sections through the Jurassic Yerington batholith and surrounding rocks. Cross sectional exposures of the composite batholith that hosts and underlies the Cu deposits and related porphyries, including part of the batholith floor, are now exposed, as are a complex of volcanic rocks that were deposited on the surface above. Together with mapped age relationships (Proffett and Dilles 1984), and radiometric age determinations (Dilles and Wright, 1988 and the present study), these exposures provide a unique four dimensional picture of an upper-crustal magmatic system and related porphyry copper mineralization. The total amount of crust exposed extends from the Jurassic surface to as much as 8 to 10 km below. Much is understood about the district from past work, but much of this work has not been published. The work supported by the grant was directed toward preparing some of the work already done for publication and toward acquisition of additional data needed for an improved understanding of petrologic processes involved in genesis of the porphyry copper deposits and associated geologic systems. A summary of results follows in section 2, which is then followed by sections describing some of the results in more detail.

2. SUMMARY

The Yerington batholith (Proffett and Dilles, 1984) is a composite batholith more than 15 km in diameter when the effects of late Cenozoic basin and range extension are removed. The oldest rocks of the batholith are small bodies of hornblende gabbro 300 m or less in size. These were followed by a large mass of biotite-hornblende quartz monzodiorite which comprises most of the outer and pre-tilt upper part of the batholith, and within which internal contacts indicate it was emplaced as several plutons. Hornblende quartz monzonite was intruded into the quartz monzodiorite, and its distribution suggests that it was also emplaced as several plutons. The youngest major pluton is of biotite-hornblende porphyritic granite with large K-feldspar phenocrysts in a medium-grained, equigranular groundmass, and is centered within the batholith. No internal contacts have been found within this pluton, suggesting that it formed as a single magma chamber. Near the top of the porphyritic granite pluton, and above it, are numerous dikes and small stocks of granite porphyry that are similar in mineral and chemical composition to the porphyritic granite, but in which part of the quartz and K-feldspar occurs as a fine grained matrix instead of the coarse-grained interstitial quartz and K-feldspar of the porphyritic granite. These appear to have been derived from the porphyritic granite magma chamber, and the porphyry copper deposits of the district are associated with them. Above (pre-tilt) most of the batholith are a section of volcanic rocks (Proffett and Dilles, 1991, 2007), including a lower part with compositions and age constrains similar to the quartz monzodiorite of the batholith (Artesia Lake Volcanics) and an upper part which include units with compositions, phenocrysts and age constrains similar to the granite porphyry (Fulstone Spring Volcanics). Following are descriptions of new results within this framework from work supported by grant 06HQGR0171. Locations are shown on Figure 2.1.

Yerington batholith emplacement processes: Mapping near the floor of the Yerington batholith at Luhr Hill (see map and more detail in section 3 of this report) has identified what appear to be multiple feeders for the quartz monzodiorite, supporting the interpretation that this phase of the batholith was emplaced as multiple plutons. Quartz monzodiorite near the southern contact of the batholith in the central Singatse Range (see section 4) locally contains xenoliths of other phases of quartz monzodiorite that are similar, but distinct.

Additional observations in the Luhr Hill porphyritic granite, as in previous work, has not revealed internal contacts within this pluton, and has shown that this unit is very uniform in character in all known exposures, including the Singatse Range southeast of Mickey Pass (Fig. 4.1), small exposures just east of the Yerington Mine and Luhr Hill (Fig. 3.1). This supports the interpretation that this pluton once existed as a single continuous magma chamber.

Role of mafic magma: Observations in exposures of the batholith floor in the eastern part of Luhr Hill (Section 3), and on the distribution and character of mafic xenoliths throughout the batholith, indicate little or no evidence for the injection of mafic magma into the magma chamber represented by the porphyritic granite pluton. There appears to be little evidence that mafic magma had a significant role in development of porphyry copper mineralization associated with granite porphyries above the pluton, or of eruption of volcanic rocks related to the pluton.

Wall rocks and floor rocks: Mapping, field checking and petrographic work on the rocks that form the floor and deep walls of the Yerington batholith (Sections 3 and 4) shows that the uppermost part of the Triassic to Lower Jurassic section has been partly domed up above the batholith and that most of the section has been depressed downward by the batholith. A volume of Triassic to Lower Jurassic stratified rocks equal to roughly 15 to 30 percent of the volume of the batholith is missing where the batholith is now located. Lack of evidence for “stoped” blocks in the batholith indicates that this volume was apparently assimilated by the batholith. Work is in progress to update paleogeologic sections based on previous and new observations in order to improve constraints on the volume and composition of assimilated rocks and on petrographic work and analysis of geochemical data to evaluate effects of assimilation on the rocks of the batholith.

Compilation of Buckskin Range mapping: Field mapping that had been done in the Buckskin Range (Proffett and Dilles, unpublished) had been compiled and part of it had been digitized before work supported by the grant was begun, and the remainder of the available mapping, comprising the southern Buckskin Range, has now been digitized (section 5, Fig. 5.1). Available funds permitted only limited new mapping to be completed in the Buckskin Range, so a few unmapped area still remain on the Buckskin maps. (Note that original, pre-IUGS, rock nomenclature was used on the Buckskin Maps, Figs. 5.1 and 6.1, so that quartz monzonite porphyry, Jqmp, on the Buckskin maps is equivalent to IUGS granite porphyry, and granodiorite, Jgd, on the Buckskin maps is equivalent to IUGS quartz monzodiorite. All units will be changed to IUGS nomenclature before submittal for publication).

Jurassic volcanic rocks: The Jurassic Artesia Lake Volcanics, well exposed in the Buckskin Range west of Yerington, appear to be volcanic equivalents of some phases of the quartz monzodiorite of the Yerington batholith, and some units of the overlying porphyritic volcanic rocks of the Jurassic Fulstone Spring Volcanics may be volcanic equivalents of some of the granite porphyries of the Yerington batholith. However, there has long been doubts about the important relationship between granite porphyry and Fulstone volcanic units because of what has appeared to be conflicting evidence (see section 6). Therefore as part of this study a sample was taken of one of the units within the Fulstone Spring Volcanics, zircons were separated at Oregon State University (under direction of John Dilles), and U-Pb ages were measured on the USGS-Stanford SHRIMP-RG under the direction of Joe Wooden, director of the facility (see section 6). The results indicate an age of 167.8 ±1.2 Ma, within analytical uncertainty of a previous U-Pb zircon age of 168.5 ±0.4 Ma for granite porphyry in the Yerington batholith (Dilles and Wright, 1988), and are consistent with the interpretation that some of the lower units of the Jurassic Fulstone Spring Volcanics are indeed volcanic equivalents of some of the granite porphyries of the Yerington batholith (see section 6 for further details).

Field checking in Wassuk Range: The eastern part of the Yerington batholith complex is exposed in the northern Wassuk Range east of Yerington. Field checking of existing mapping there indicated that it would be important to remap certain restricted areas in more detail in order to clarify the identity of certain rock units and important structural relationships. Plotting and analysis of the results are in progress, but preliminary results are briefly summarized in section 7.

Interpretation of mapping and construction of paleogeologic maps and sections: A series of maps and sections which show the geology as it was before late Cenozoic extensional faulting and tilting was constructed during previous work (Proffett, 1991 and earlier, unpublished). The new results require revisions to these maps and sections, which is in progress, along with construction of additional maps and sections.

3. EASTERN LUHR HILL

As was first noticed by Hunter Ware (1972, unpublished report for The Anaconda Company), in the eastern part of Luhr Hill the bottom of the west-tilted Yerington batholith is exposed, and floor rocks of the batholith are exposed to the east. This section of the batholith floor extends for about 2 km in a north-south direction. A few days were spent mapping in detail in this area in 2000 and 2007 (Fig. 3.1).

Pre-Batholith Rocks

Older rocks exposed east of (pre-tilt below) the floor of the batholith include meta-andesite, metarhyolite and white, mafic-poor granite. The meta-andesite and metarhyolite are very similar to lithologies found in the Middle or earliest Late Triassic McConnell Canyon Volcanics (Proffett and Dilles, 2007, in press), which comprise the oldest rocks exposed in the Yerington district. Included with these are small exposures of a distinctive quartz porphyry, similar to quartz porphyry which intrudes the McConnell Canyon Volcanic section (Proffett and Dilles, 2007, in press) from which a U-Pb zircon age of about 232 Ma has been reported (Dilles and Wright, 1988). The lithologic similarity and the presence of the quartz porphyry indicate that the floor rocks of the batholith in the eastern part of Luhr Hill are very likely correlative with the McConnell Canyon Volcanics. These metavolcanics in the eastern part of Luhr Hill are overprinted by a strong deformational foliation.

The white granite that comprises parts of the floor rocks of the Yerington batholith intrudes the meta-andesite and metarhyolite and is intruded by quartz monzodiorite of the Yerington batholith. It is therefore apparently of Late Triassic or Early to Middle Jurassic age. Chemical analyses done in 2000 (Table 3.1, Y00-1, Y00-7) indicate trace element signatures, such as low Sr/Y, that are very different from those of the Yerington batholith, but which are similar to those of the Triassic metavolcanics (Table 3.1, Y00-5, Y00-6) and other Triassic rocks of the district (see for example Dilles, 1984, Table 5). This granite contains a small amount of biotite as the main mafic mineral and is rich in quartz. In most exposures it is overprinted by a deformational foliation.

Gabbro

Some small bodies of gabbro (Jgb), two of which are large enough to show on the map, are exposed within the floor rocks of the batholith. The southernmost exposure and smaller exposures nearby clearly intrude the Triassic rocks and the associated white granite described above, and where they do, they are not overprinted by the deformational foliation that overprints these older rocks. A small isolated exposure of hornblende gabbro 760 m to the north contains what appears to be metamorphic biotite that partly replaces the hornblende, and does not resemble the layered gabbro found in the Yerington batholith in the Singatse Range to the west (Proffett and Dilles, 1984). A chemical analysis of gabbro from this exposure done in 2000 (Table 3.1, Y00-8) indicates lower Sr than a Singatse Range gabbro of comparable silica content (unpublished analyses by The Anaconda Co., 1971). It is questionable as to whether these gabbros might be related to the Triassic Wassuk Diorite (Dilles, 1984; Dilles and Wright, 1988), the Jurassic Yerington batholith or neither.

Yerington Batholith

Quartz monzodiorite: Quartz monzodiorite ("Jqmd", but shortened to "Jqm" on Fig. 3.1, and shown using pre-IUGS rock definitions as "Jgd" by Proffett and Dilles, 1984) is the most widespread phase of the Jurassic Yerington batholith, and except for small bodies of gabbro, is the oldest phase. A U-Pb zircon age of about 169 Ma has been reported for this unit (Dilles and Wright, 1988). New mapping shows at least three east-west dike-like bodies of quartz monzodiorite that intrude Triassic rocks east of (pre-tilt below) the large body of porphyritic granite (Fig. 3.1). These are about 35 to 140 m wide and can be traced for up to about 390 m along strike. They would have been steep dikes before tilting, and were likely feeders for the much larger bodies of quartz monzodiorite in the main quartz monzodiorite part of the batholith above. Previous mapping in the Singatse Range indicates that the quartz monzodiorite consists of several individual intrusions of slightly different lithology (Proffett and Dilles, 1984). Different dikes in the floor rocks may represent feeders for different intrusions. Some small flat (pre-tilt) dike or sill-like bodies of quartz monzodiorite also occur (Fig. 3.1). Available exposures and aeromagnetic data (E.

O. MacAlister, unpublished map, The Anaconda Co., 1966) show that expansion of the quartz monzodiorite bodies from dikes to plutons took place only about 300 m west of (pre-tilt above) the floor of the porphyritic granite pluton on the south side of Luhr Hill, and about 1 km west of this floor on the north side of Luhr Hill (Fig. 3.1).

In a large part of at least one of the dike-like Jqmd bodies below (east of) the Jpg pluton (near UTM 4313678N, 318051E, NAD27-CONUS) the hornblende is altered to fine shreddy biotite. There is no evidence that this secondary biotite is related to porphyry-type potassic alteration, and it is probably metamorphic.

In some areas, such as the small hill at UTM 4316365N,315850E, small dikes of undeformed quartz monzodiorite cut strongly foliated older rocks. In other areas quartz monzodiorite is overprinted by a strong deformational foliation, and in some areas this foliation is cut by undeformed quartz monzonite (Fig. 3.2) and in others the foliation overprints both quartz monzodiorite and quartz monzonite. Foliation is generally east west in the east-west dike-like bodies and north-south in the north-south trending sill-like bodies.

Quartz monzonite: Quartz monzonite ("Jqm", but shortened to "Jq" on Fig. 3.1, also shown as "Jqm" by Proffett and Dilles, 1984) is the second major phase of the Yerington batholith. Only a few small bodies, including narrow dikes, occur in the eastern part of Luhr Hill. These are within larger quartz monzodiorite bodies, and most are too small to show on the map (Fig. 3.2). As mentioned above, some, such as shown in (Fig. 3.2), cut foliation in deformed quartz monzodiorite, and others are foliated along with quartz monzodiorite. Some such as the one in (Fig. 3.2), are oriented nearly north-south and dip steeply, so in pre-tilt orientation were thin, flat-lying dikes, whereas others are oriented east-west, so were steep dikes.

There are small bodies of Triassic metarhyolite and meta-andesite, a meter to a few meters in size, within areas of quartz monzonite and quartz monzodiorite. These are larger than the typical xenoliths found in these rocks, and appear to be relicts of wall rock that were caught between numerous dikes and other small bodies of the quartz monzodiorite and quartz monzonite. They appear to be more abundant in the western parts of the exposures than in the easternmost parts, and suggest that feeder zones widen westward (pre-tilt upward) toward the main plutons of quartz monzodiorite and quartz monzonite by increase in the number of small dikes and sills. In contrast, there are no such bodies of wall rock within the porphyritic granite pluton described below, indicating that it existed as one large magma chamber.

Porphyritic granite: Porphyritic granite ("Jpg", but shortened to "Jp" on Fig. 3.1, and shown using pre-IUGS rock definitions as "Jpqm" by Proffett and Dilles, 1984) is the youngest major pluton of the Yerington batholith. The floor of the porphyritic granite pluton is exposed for a distance of 2 km in a N 10 W (350 degrees) trend, and throughout this distance it is straight except for a few small-scale irregularities (Fig. 3.1). Where the contact with older rocks is exposed in the southeast part of Luhr Hill, it dips 62 degrees east-northeast. Reconstruction of geology as it was before late Cenozoic extensional tilting and faulting indicates that this floor was about 5.5 to 6 km below the early Cenozoic surface or 8.5 - 9 km below the Jurassic surface at the time of emplacement of the Jurassic Yerington batholith (Proffett, unpublished sections, 1991). Middle Cenozoic ignimbrites exposed in the region east and west of Luhr Hill now strike north-northwest to north-northeast, and dip steeply west in the Singatse Range west of Luhr Hill and steeply west to steeply east (overturned) east of Luhr Hill. The floor of the porphyritic granite pluton therefore had a nearly flat to possibly gentle west dip before Cenozoic tilting and faulting.

During the present work porphyritic granite was examined along the tilted pluton floor and for a distance of 300 m west of (pre-tilt above) the floor. It was found to be very uniform in composition and texture in this area, and identical to porphyritic granite in other exposures of the Yerington district, which are just east of the Yerington Mine and southeast of Mickey Pass in the Singatse Range (Proffett and Dilles, 1984). The abundance and grain size of mafic minerals (1-3 percent 1-3 mm biotite and 3-5 percent 1-3 mm hornblende) and K-feldspar phenocrysts (7-12 percent 0.5-1.5 cm) are consistent. The main variations observed, as in previous mapping, are variations in the texture of interstitial quartz and feldspar. It is uniform chemically also; for example compare sample Y00-17A from the pre-tilt top of the pluton just east of the Yerington Mine with sample Y07-38 near the pluton floor in the southeast part of Luhr Hill (Table 3.2).

The remapping shows that a separate 150 x 150 m body of porphyritic granite located about 90 m east of (pre-tilt below) the floor of the main porphyritic granite pluton (Fig. 3.1, 4314600N, 317850E) is separated from the main pluton by older quartz monzodiorite as well as by younger quartz monzodiorite porphyry. The eastern limit of this body is not exposed, but it may represent part of a feeder for the main pluton. The K-feldspar phenocrysts are slightly larger (0.7-2 cm) than those in the main pluton, and they become larger and less abundant to the east, where they locally resemble those of the more felsic phase of the quartz monzodiorite porphyry described below.

Xenoliths in porphyritic granite were also examined. They are consistently present but small (mostly 0.5 - 3 cm) and uniformly extremely sparse, even adjacent to the base of the pluton, constituting much less than ~0.1 percent of the rock (probably less than ~0.01 percent). The vast majority are very fine-grained gabbro or diorite, consisting of sub-equal amounts of mafic and felsic minerals (Fig. 3.3). They are angular to subangular, have very sharp boundaries with the Jpg host, and no evidence could be seen for deformation, partial digestion or partial melting of these xenoliths. Near the base of the pluton there are also very rare xenoliths of medium-grained gabbro and of metarhyolite like that exposed in below the pluton floor. One xenolith was observed about 10 meters above the floor of the Jpg pluton which is about 3 x 10 cm in size, appears to be flattened in a N5°E, 35°-40° NE plane and consists of medium grained granodiorite. It consists of 0.5-1 mm plagioclase, hornblende, biotite, sphene, magnetite and rare 1 cm K-feldspar, and it has very diffuse boundaries and appears to be partly digested by the Jpg host. It somewhat resembles some of the less-mafic phases of the "Jqmdp" flat-lying dikes along the floor of the Jpg pluton nearby, except that it appears to contain more sphene. No other xenoliths like this have been found in the pluton.

No evidence was found that mafic magma was emplaced into the floor of the Jpg magma chamber, such as has been well documented in certain other felsic plutons (Wiebe, 1996). The mafic xenoliths could represent the frozen, fragmented and dispersed remains of such an injection, but the uniform distribution of these and their extremely low abundance indicates that if any injection took place, it was early in the history of the magma chamber, and was insignificant in amount. A rough estimate of the volume of these xenoliths and the size and volume of the pluton indicates that the xenoliths would be equivalent to a mafic layer 0.3 m thick spread over the floor of the pluton. If such injection happened at all, it is unlikely to have had any role in porphyry copper genesis.

<u>Granite porphyry</u>: Granite porphyry dikes and small stocks are that latest significant intrusive phase of the Yerington batholith. These are petrographically similar to the porphyritic granite, having phenocrysts of K-feldspar, plagioclase, hornblende, biotite and quartz similar to the euhedral phases of the porphyritic granite, and differing mainly in having a groundmass of fine-grained quartz and feldspar between these phenocrysts whereas the porphyritic granite has coarse-grained interstitial quartz and alkali feldspar between the euhedral phases. Granite porphyry dikes and stocks occur in the upper part of the porphyritic granite pluton and in the roof rocks above, and none were found in the floor zone mapped in the eastern part of Luhr Hill. One WNW trending dike previously mapped as granite porphyry in the area (Proffett and Dilles, 1984, "Jqmp" on that map; UTM 4313910N, 317740E) was reexamined and found to be quartz monzodiorite (discussed

below). Some dikes mapped as granite porphyry on the southwest part of Luhr Hill (Proffett and Dilles, 1984) have not yet been reexamined.

Quartz monzodiorite porphyry

Quartz monzodiorite porphyry ("Jqmdp", but shown by Proffett and Dilles, 1984, using pre-IUGS rock definitions as "Jgdp"; for shortened abbreviations for the different phases on Fig. 3.1 see below) dikes with sparse, large K-feldspar phenocrysts are widespread but not abundant in the Yerington district. They cut all rock units of the Yerington batholith but are apparently cut by the slightly younger Shamrock batholith. They occupy major Jurassic east-west faults that occur north and south of the Yerington batholith, and a U-Pb zircon age of about 165 Ma has been reported form a dike of quartz monzodiorite porphyry in the Buckskin Range. Some steep north-south dikes of quartz monzodiorite porphyry occur in the rocks east of the floor of the Yerington batholith (pre-tilt below) in eastern Luhr Hill (Proffett and Dilles, 1984), and some time was spent remapping these rocks.

The steep, north-south dikes would have been nearly flat-lying dikes before late Cenozoic tilting, and some were emplaced along the floor of the porphyritic granite pluton, while others, as shown by the new mapping, were emplaced some distance below the floor.

The contact between the floor of the Jpg pluton and the Jqmdp below was observed in only one place, a rough dirt road at UTM 4314396N, 317722E (Fig. 3.4). Here the contact is subtle, as the adjacent Jqmdp (most felsic phase described below) is similar in composition to the Jpg, but the contact can be seen to dip steeply west. There are no features truncated at the contact. The Jqmdp contains fewer, but larger K-feldspar phenocrysts than the Jpg, and slightly more mafics. The Jqmdp appears to be slightly finer-grained and contain slightly more mafic minerals than usual in a zone a few mm to cms wide adjacent to the contact, possibly a contact effect indicating that the Jqmdp is younger than the Jpg. There also appears to be a small dikelet of Jqmdp cutting the Jpg.

There are at least three phases of Jqmdp, which increase in mafic content downward from the floor of the Jpg pluton. All three phases are exposed near a shallow gully near UTM 4314730N, 317710E. Here the westernmost, most felsic phase of the Jqmdp ("jpf" on Fig. 3.1) is about 60 meters thick. Its western contact with Jpg is not exposed. This phase contains 2 to 5 percent 0.5 - 4 cm rectangular, purple to white K-feldspar phenocrysts which contain abundant mineral inclusions (compared to 5-10 percent 0.5-1.5 cm K-feldspar phenocrysts in Jpg, with only rare mineral inclusions) and 15 to 20 percent 1-7 mm mafic phenocrysts (compared to 7 to 10 percent mafic phenocrysts in Jpg). Jqmdp also contains less visible sphene than Jpg. This phase of Jqmdp has few xenoliths, although it contains more than does the Jpg. Those that are present are a little more mafic and finer grained than the host, and in a few places there are a few diffuse layers and lenses of more mafic material that may indicate mixing of magma or assimilation of xenoliths. Very rare patches of Jpg occur in this felsic phase of the Jqmdp south of here; these appear to be xenoliths rather than apophyses because the Jqmpd has what appears to be a fine-grained, mafic-rich "chilled" margin where it contacts the Jpg patches (Fig. 3.5). In some cases Jpg appears to be partly digested by Jqmdp.

Below (east of) the felsic phase is a phase of intermediate mafic content about 60-70 meters thick ("Jpi" on Fig. 3.1). The contact between this phase and the felsic phase to the west is diffuse over several mm to several cm, and in some places the two rocks appear to be interlayered in 5 to 20 cm layers (Figs. 3.6). A dike of Jqmdp similar in composition to this intermediate phase intrudes and cuts across a large part of the porphyritic granite body. The intermediate phase contains 0.5 to 3 percent 0.5 - 4 cm subhedral K-feldspar phenocrysts and 20 to 25 percent mafic minerals, but otherwise is similar to the felsic phase to the west. It also contains more abundant mafic to intermediate composition xenoliths (overall 1-3 percent xenoliths, but variable), which are finer-grained than the host and which contain a few feldspar phenocrysts (Fig. 3.7). Many of these are subrounded but others are flattened or elongated, and appear to have been deformed, probably because of partial melting. Xenoliths of wall rock, such as Triassic meta-andesite and metarhyolite, a few cm to more than a meter in size, are also common throughout the intermediate phase of Jqmdp.

The most-mafic phase ("Jpm" on Fig. 3.1), to the east of the others, contains abundant plagioclase phenocrysts, commonly up to 0.5 -1 cm in size, as well as hornblende, biotite and magnetite phenocrysts. Most of it contains no large K-feldspar phenocrysts, though a very few (< 0.5 percent) large K-feldspar phenocrysts occur near its contact with the intermediate phase of Jqmdp. These resemble the large ones in the other two phases of Jqmdp rather than those in the porphyritic granite, and their occurrence only near the contact with the intermediate phase of Jqmdp and their sometimes broken appearance suggests that they are xenocrysts rather than a primary crystallized phase of the mafic Jqmdp.

The mafic phase of Jqmdp contains more abundant xenoliths than the other phases. Most of these consist of fine-grained mafic rock with sparse plagioclase and mafic phenocrysts, and many of them appear to be deformed and partly melted or assimilated (Fig. 3.8). Xenoliths of wall rock, such as Triassic meta-andesite and metarhyolite, are also common. In the eastern (pre-tilt lower) exposures of the mafic phase of Jqmdp much of the rock is strongly foliated, and contains deformed and flattened xenoliths of fine grained mafic rock and of the quartz monzonite phase of the Yerington batholith (Fig. 3.9).

The Jqmdp comprises a complex of irregular flat-lying dikes, which was emplaced along and below the basal contact of the Jpg, and which consists of at least three phases that increase in mafic content downward, toward the floor rocks, and which increase in the content of large K-feldspar phenocrysts upward, toward the Jpg. Perhaps this complex formed through injections of more mafic magma into a flat-lying body of more-felsic, K-feldspar-bearing Jqmdp magma, but this apparently happened after crystallization of the Jpg, as the Jpg rocks do not appear to have been affected by these magma injections. However, the presence of what appear to be xenoliths of the Jpg, some of which appear to be partly digested, and the increase in abundance of K-feldspar phenocrysts and more felsic composition in the phases of Jqmdp nearest the Jpg, suggest that K-feldspar and possibly other phenocrysts in the Jqmdp may have formed by assimilation of Jpg. This may have happened through incorporation of Jpg xenoliths in the Jqmdp, most of which may have been assimilated due to their likely lower melting temperature than the more-mafic Jqmdp magma. However, the dike of intermediate-composition Jqmdp (Fig. 3.1) cutting across a large expanse of Jpg indicates that the Jpg was well solidified by the time of emplacement of the intermediate composition Jqmdp.

Samples for polished thin sections have been collected of the phases of the Jqmdp and nearby Jpg, to look for evidence of relicts from assimilation of both Jpg in Jqmdp and of more mafic xenoliths in Jqmdp. Minerals such as zircon will especially need to be examined for this. The larger size of, and more abundant mafic inclusions in, Jqmdp K-feldspar phenocrysts than Jpg K-feldspar phenocrysts, might argue against the idea that those in Jqmdp originated by assimilation of Jpg. However, many of the large K-feldspar phenocrysts in Jqmdp have a 0.5-1.5 cm core that is clean of mafic mineral inclusions, surrounded by zones with more abundant such inclusions. Possibly the K-feldspar phenocrysts grew after being assimilated, and while growing, incorporated mafic inclusions from the more-mafic Jqmdp magma. In thin section this might be evident as "unconformities" in the growth patterns of the K-feldspar phenocrysts.

Aplite and Pegmatite

Small dikes and irregular bodies of aplite and pegmatite cutting the lower part of the porphyritic granite are common. Where they are common elsewhere in the Yerington district, such as in and near the upper part of the porphyritic granite pluton, they are thought to be related to late-stage magmatic activity of the porphyritic granite. However, in eastern Luhr Hill these aplites and pegmatites also commonly cut the quartz monzodiorite porphyry bodies (Fig. 3.10), and so here are distinctly younger than the porphyritic granite. They may be the result of late stage magmatic activity related to the quartz monzonite porphyry.

Later Intrusions

Many of the bodies shown on the Proffett and Dilles (1984) map in the east part of Luhr Hill as “Ja” have been found to contain bright, fresh hornblende needles (such as at UTM 4314515N, 317955E, and 4314715N, 317615E). At UTM 4314730N, 317850E there is a dike of this andesite that dips gently east, steep in pre-tilt orientation. Hornblende needles such as these have not been previously found in Jurassic andesite dikes, but are common in Miocene andesites, and it is likely that these intrusions are Miocene rather than Jurassic.

Structure

The oldest structures are a well developed metamorphic foliation in the Triassic metarhyolite, meta-andesite and granite, designated on Figure 3.1 as “metamorphic foliation”. This is not always possible to distinguish from the other foliations, but in some areas it is truncated by gabbro or intrusive rocks of the Yerington batholith which are themselves unaffected by the foliation. It is commonly subparallel to contacts between meta-andesite and metarhyolite, which in many areas strike north-south and dip steeply, but in a few areas it strikes approximately east-west. This foliation is most commonly defined by biotite orientation, but in some cases also by other minerals.

Although various intrusive rocks truncate the metamorphic foliation in Triassic rocks, some of these intrusive rocks are themselves overprinted by a foliation. This foliation is usually defined by secondary biotite that appears to be of metamorphic origin. It appears to be the result of deformation of the intrusions, but the nature of this deformation is not well understood. It is called “deformational foliation” on Figure 3.1 to distinguish it from the other foliations. Quartz monzodiorite of the Yerington batholith is commonly foliated and the foliation is oriented more or less north-south in north-south bodies and east-west in east-west bodies. Foliation in quartz monzodiorite is sometimes truncated by non-foliated quartz monzonite (Fig. 3.2) and in other exposures quartz monzodiorite and quartz monzonite are both foliated. Deformational foliation in quartz monzodiorite and quartz monzonite are usually truncated at intrusive contacts with quartz monzodiorite porphyries, which themselves are rarely overprinted by deformational foliation. Porphyritic granite also is almost never foliated, but at 4314300N, 317670E there is a small area that appears to be a body of porphyry overprinted by foliation.

Igneous layering and foliation that appears to have formed when the rock was still partly molten is common in quartz monzodiorite porphyry, and is shown as “igneous foliation” on Figure 3.1. It commonly strikes north-south, and dips moderately to steeply west, at an angle to deformational and metamorphic foliations, which commonly dip very steeply west to east.

East-west trending dike-like bodies of quartz monzodiorite of the Yerington batholith cut across north-south contacts between Triassic rocks and the associated metamorphic foliation (such as near 4314425N, 317915E, Figure 3.1) without reorienting or otherwise deforming the older metamorphic foliation. This seems to be more consistent with the interpretation that these bodies were feeder dikes through which magma was emplaced into the plutons above, rather than the interpretation that the plutons above were emplaced as diapirs, and that the east-west bodies of quartz monzodiorite represent “tails” of the diapirs.

4. CENTRAL SINGATSE RANGE

Previous mapping in the central part of the Singatse Range, including the southern part of the Yerington batholith, the Triassic-Jurassic section to the south, and the Shamrock batholith south of those, has been compiled, checked and digitized to help in evaluating emplacement and crystallization processes in the batholith and to help in construction of a north-northwest paleogeologic cross section through this part of the batholith (Fig. 4.1). A recent traverse through the quartz monzodiorite near the southern contact confirms previous observations that there are multiple phases with slightly different, though distinct characteristics. Near UTM 4314928N, 305580E the main phase of quartz monzodiorite contains rounded 20-50 cm xenoliths of slightly coarser-grained quartz monzodiorite and of a slightly finer-grained, sub-porphyritic quartz monzodiorite (Fig. 4.2). The finer-grained sub-porphyritic xenoliths have a few small veinlets of amphibole, feldspar, quartz and epidote that are truncated at the contact with the host phase, and somewhat resemble the Artesia Lake Volcanics. These xenoliths may represent parts of early quartz monzodiorite phases that were feeders for some of the earlier units of the Artesia Lake Volcanics.

Though xenoliths and internal contacts are found locally in quartz monzodiorite of the Yerington batholith, most parts of any given phase are quite uniform in character, with little heterogeneity on an outcrop scale or on the scale of an area of several outcrops. Most quartz monzodiorite contains few xenoliths (usually less than 0.5 percent) and those that are present are generally small (less than 2 cm) and of a mafic lithology with a high proportion of mafic minerals (mostly hornblende and minor magnetite and biotite). Most xenoliths have sharp boundaries, and only a few appear to have been partly digested. In addition to xenoliths, there are commonly small clots of mafic minerals, some of which are biotite-rich and some of which consist of clusters of hornblende, sphene, magnetite and plagioclase. These could possibly be relicts of partly digested xenoliths, or possibly relicts left from assimilation of wall rock, and they are undergoing continued study.

A weak foliation and lineation, defined by orientation of hornblende, is common in quartz monzodiorite near the southern contact of the batholith, and at the locality described above, overprints the main phase of the quartz monzodiorite as well as both types of quartz monzodiorite xenoliths (though the shapes of the xenoliths are not deformed). This relationship indicates that this foliation could not be of primary igneous origin, and must have formed by later deformation. This foliation is approximately parallel to bedding and foliation in Triassic rocks near the batholith to the south (Fig. 4.1).

Petrographic examination shows that quartz monzodiorite in more easterly exposures (pre-tilt deeper) show no evidence of the growth and oscillatory zoning in plagioclase that is typical of rocks of this type, but are simply gradually zoned from somewhat more calcic compositions in interiors to somewhat more sodic compositions in outer parts. However, what appear to be relict growth zones defined by small inclusions, but no longer by composition, occur in some grains. In more westerly exposures (pre-tilt shallower) a few plagioclase grains preserve relicts of growth zones, including some that appear to be oscillatory, but these are not sharply defined. In some cases they appear to be partly replaced by unzoned plagioclase and in others the zones seem to simply fade into unzoned plagioclase (Fig. 4.3). These features suggest that plagioclase has lost its zoning, and may be evidence that the quartz monzodiorite experienced elevated temperatures for a significant period of time after it was emplaced. This, along with the foliation described above, is evidence that the quartz monzodiorite underwent at least mild metamorphism and minor deformation since it was emplaced.

A traverse was also made through the cupola of porphyritic granite southeast of Mickey Pass. Existing mapping was confirmed or modified slightly. The porphyritic granite was found to be very similar in all respects to that in other areas, the main variation found, as in previous work, being the change in grain size of the interstitial anhedral quartz and K-feldspar between the more euhedral plagioclase, mafic minerals and large K-feldspar phenocrysts. The anhedral interstitial quartz and feldspar becomes finer-grained approaching the roof of the pluton.

Granite porphyries show somewhat more variation in texture than the porphyritic granite. A significant finding in samples of granite porphyry taken for petrographic work is that some of the zircon grains have what appear to be older cores surrounded by overgrowth zones (Fig. 4.4). The examples in Figure 4.4 are from a sample near the site sampled for a U-Pb zircon age reported by Dilles and Wright (1988), and because the age measurements were on whole zircon grains, the reported age could be older than the emplacement age of the porphyry. This observation is consistent with new work by John Dilles (personal communication) suggesting more than one age population in the Yerington district samples.

5. SOUTHERN BUCKSKIN RANGE MAPPING

Rocks of the Buckskin Range, like those in the rest of the Yerington district, have been tilted steeply westward and displaced by east-dipping normal faults as a result of late Cenozoic basin and range extension. The uppermost parts of the Jurassic Yerington batholith, and volcanic rocks of age similar to the batholith (Proffett and Dilles, 2007) are exposed there. Figure 5.1A shows the results of detailed mapping of the southern part of the range, and Figure 5.1B is an explanation of the map units (see Figure 6.1 for the northern part of the range).

6. AGE OF FULSTONE VOLCANIC UNIT IN BUCKSKIN RANGE

The Jurassic Artesia Lake Volcanics appear to be volcanic equivalents of some phases of the quartz monzodiorite of the Yerington batholith, and are well exposed in the Buckskin Range west of Yerington. These are overlain by the Jurassic Fulstone Spring volcanics, a sequence of porphyritic volcanic rocks (Figs. 6.1, 6.4). Some units of the Fulstone Spring Volcanics, especially in the lower part of the section, contain phenocryst similar in identity, abundance and size to the those in many of the Jurassic granite porphyries, and they also have similar age constraints. However Dilles and Wright (1988) measured a U-Pb age of 166.5 Ma on zircons from Fulstone Volcanics in the upper part of the section (sample BK45; see Fig. 6.1A for location, Fig. 6.4 for stratigraphy), a little older than a 168.5 Ma age they measured on zircons from a granite porphyry from the Yerington batholith, but analytically similar to an age they obtained for the Shamrock batholith to the south. This lead these authors to a preliminary interpretation that the Fulstone Spring Volcanics may be cogenetic with the Shamrock batholith rather than the granite porphyries of the Yerington batholith. Problems with this interpretation are that in the Pine Nut Range to the west, the Shamrock batholith cuts cleanly across the entire exposed Fulstone Spring volcanic section there at a high angle, and causes contact metamorphism in the adjacent Fulstone Spring volcanic rocks. Also the Fulstone Spring Volcanics are cut by dikes of Jurassic quartz monzodiorite porphyry, which elsewhere in the district appears to be cut by the Shamrock batholith. The Shamrock batholith also differs somewhat in certain geochemical characteristics, for example in having relatively low Sr/Y, whereas the Fulstone Spring Volcanics, like all of the units of the Yerington batholith, have high Sr/Y (Table 3.2, sample Y07-60).

Detailed mapping shows that a dike of Jurassic granite porphyry (Jqmp on Fig. 6.1) that cuts Artesia Volcanics in the Buckskin Range can be followed westward (pre-tilt upward) to a flow of volcanic porphyry (Jfq) in the lower part of the Fulstone section that is similar in phenocryst content to the granite porphyry dike (Fig. 6.1A, just SE of center). A sample, Y07-60 (UTM - NAD27: 4325771N, 296825E, see Fig. 6.1 for location), of the Fulstone porphyritic flow (unit Jfq on Fig. 6.1; unit “2” of Fulstone Spring Volcanics on Fig. 6.4) was taken for U-Pb zircon age determination, and the age was measured using the USGS-Stanford SHRIMP-RG under the direction of Joe Wooden, director of the facility, as part of this study. Details are given below.

Analytical Procedures

Zircon grains were separated from the rock sample by John Dilles and Rob Lee at Oregon State University. The rock samples were broken with a hammer, crushed, and ground in a steel disk grinder, then the heavy minerals were separated using a Wilfley shaking table, heavy liquids and a Frantz magnetic separator. Final separation of zircons was accomplished by hand picking under a binocular microscope. Special care was taken to clean the grinding machines (via compressed air), Wilfley table (via washing the epoxy table top and hoppers thoroughly), and the Frantz (via brush and compressed air).

The zircon grains were mounted in epoxy on a disc-shaped mount, 25.4 mm diameter and 6 mm thick, by Rob Lee and B. J. Walker under the direction of Frank Mazdab and Joe Wooden at the USGS-Stanford SHRIMP-RG facility, then polished, photographed in reflected light, coated with a thin layer of gold to provide an electrically conductive surface, and photographed in cathodoluminescence (CL) on a scanning electron microscope (SEM). CL reveals patterns of growth zoning, recrystallization, dissolution, alteration and re-growth within the grains (Fig. 6.2).

The zircons on the disk-shaped mount were mounted in the SHRIMP-RG sample holder, left overnight in the instrument’s vacuum, and then set up for analysis, and the instrument was adjusted for operation, all by Joe Wooden. Spots about 30 microns in diameter on the polished surface of the zircon grains were selected for analysis, based on zoning revealed in the CL images, by John Proffett, John Dilles and B. J. Walker (Fig. 6.2). Analysis of each 30 micron diameter spot took 15-25 minutes; counting of the secondary ions begins after the spot has been bombarded for a few minutes to clean the sample surface. Elements and isotopes analyzed include ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{238}U, U, Th, La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, Zr and Hf. Ions of each specific mass are counted sequentially by a sensitive ion counting detector for several seconds (typically, in these analyses 10 sec for ^{238}U, 12 to 15 sec for ^{206}Pb, and shorter count times for other masses). The SHRIMP RG was set to make five or six scans for each spot analyzed and the results of these scans are averaged by the machine’s software. The analyzed spot is typically only 1-2 microns deep, which minimizes errors that might result from growth zones that dip at a low angle to the polished surface of the sample. “Standard” zircon grains of known composition and age were also placed on the disk-shaped mount with the samples, and spots on these were analyzed with the same procedure, and were interspersed every fifth spot analyzed with analyses of the samples. The standards used were zircon from a 419 Ma quartz diorite from Vermont for U-Pb ages and a 560 Ma placer gem zircon from Madagascar for concentrations of rare earth elements and other trace elements.

All data was inspected by Joe Wooden and subject to various tests, and problematic analyses were rejected. Rejected analyses include those that are obviously inherited (such as xenocrysts retained in the magma from melting of older rocks) and those that have suffered Pb loss. Analyzed spots, after corrections are made based on analysis of the standards, that appear to form coherent groups were used to calculate the age, and in the case of sample Y07-60, the coherent group included 7 of 15 spots analyzed (Table 6.1; Fig. 6.3). ^{204}Pb was very low in most analyses, and the most useful ages were those calculated from ^{206}Pb/^{238}U, corrected for common lead (non-radiogenic lead) using measured ^{207}Pb/^{206}Pb ratio and the assumption of concordance.

Results

The results indicate an age of 167.8 ±1.2 Ma, based on seven of the fifteen analyzed spots (Fig. 6.3). At least two zircon spots have slightly younger ages, apparently due to Pb loss, and there are six slightly older zircons that appear to represent a distinct population that were apparently inherited. These results, together with new data on the Yerington batholith granite porphyry that indicates that it may contain some older inherited zircon grains and cores (Dilles, 2007, personal communication and this study), indicates that ages of zircons from the Fulstone Jfq unit and from the granite porphyry of the Yerington batholith overlap in age within analytical uncertainty, and along with evidence described above, supports the interpretation that these rocks are cogenetic.

NORTHERN WASSUK RANGE

The eastern part of the Yerington batholith is exposed in the northern Wassuk Range east of Yerington, where it intrudes metavolcanic and metasedimentary rocks. While the ages of most of these rocks are now well constrained (Proffett and Dilles, 2007, in press) remapping of small areas 3 km north of Black Mountain and just northwest of the Northern Lights Mine was undertaken in order to clarify age relationships there. It is important to understand whether rocks in this section are from deep in the Triassic section, or are from the uppermost Triassic to Early or Middle Jurassic part of the section, for reconstruction of the pre-tilt, pre-extensional geometry. If only the lower part of the Triassic section is exposed in these areas, this would indicate gentle, but consistently westward tilt of the batholith before the late Cenozoic tilting related to extensional faulting. If latest Triassic or Jurassic rocks also occur, that would indicate that the east part of the Yerington batholith was tilted gently east, indicating a broad doming across the batholith before the late Cenozoic tilting and faulting.

North of Black Mountain

Three km north of Black Mountain quartz monzodiorite of the Jurassic Yerington batholith intrudes a sequence which contains a thin limestone with volcanic rocks both to the west (pre-tilt above) and to the east (pre-tilt below). The limestone resembles the Early to Middle Jurassic Ludwig Limestone (Proffett and Dilles, 1988), but sufficient information is not available to confirm its age, and it could be one of the Triassic limestone units. A sample that contains badly broken fossil fragments was collected and a small amount dissolved in dilute acetic acid. No conodonts have yet been found in the residue, but more work is needed on this sample.

New mapping (plotting and interpretation in progress) confirms previous observations that the volcanic rocks west of the limestone are quite different than those east of the limestone. Those east of the limestone are very similar to Triassic volcanic rocks elsewhere, such as the McConnell Canyon Volcanics (Proffett and Dilles, 2007, in press). They are rhyolitic to andesitic and have very sparse to moderately sparse amounts of plagioclase phenocrysts, and in some cases quartz phenocrysts, and appear to be strongly metamorphosed, with abundant metamorphic biotite. They are variable in character and include tuffs, tuffaceous sedimentary rocks and breccias. Volcanic rocks west of the limestone are more uniform in character, and include mostly massive rocks and breccia. They contain very abundant small plagioclase phenocrysts and abundant biotite and epidote of metamorphic origin. Some of the massive rocks are intrusive, and where rocks similar to these occur east of the limestone, they are intrusive also. The volcanic rocks west of the limestone somewhat resemble fine-grained phases of the quartz monzodiorite of the Yerington batholith, but a chemical analysis indicates different trace element abundances (for example, low Sr/Y, compared to high Sr/Y in quartz monzodiorite of the Yerington batholith).

A sample of the volcanic rocks west of the limestone was sent to Oregon State University for mineral separation, but it was possible to separate only six small zircon grains. These were analyzed for U-Pb age determination on the USGS-Stanford SHRIMP-RG under the direction of Joe Wooden. Of the six spots analyzed, two gave Triassic ages, three gave mid-Jurassic ages and one gave a late Cretaceous age. The late Cretaceous age is clearly from a contaminant grain, and the other ages may be also, a serious problem with samples that have little zircon. The results are therefore not usable at this time. Further work is in progress to attempt to identify rocks more suitable for age determination.

Northern Lights Mine

The Jurassic Ludwig Limestone and underlying Jurassic-Triassic Gardnerville Formation are exposed at the Northern Lights Mine (Proffett and Dilles, 2007, in press), and volcanic rocks occur west of the Ludwig Limestone (pre-tilt above). The section that contains the Ludwig Limestone and Gardnerville Formation is in major fault contact to the north with volcanic rocks that resemble some of those in the Triassic or possibly earliest Jurassic section elsewhere. An important problem to be clarified is whether or not the volcanic rocks west of the Ludwig Limestone are part of the same sequence of Triassic to possibly earliest Jurassic of rocks found north of the major fault, or are part of a separate, possibly Jurassic age section. If they are part of the same sequence, that may be evidence that the entire block north of the major fault, which would probably include the east part of the Yerington batholith in its north part, has been faulted upward (in pre-tilt orientation) relative to the Early to Middle Jurassic section at the Northern Lights Mine. This would favor the interpretation that the Yerington batholith in the Wassuk Range is exposed at a relatively deep level. If the volcanic rocks west of the Ludwig Limestone are part of a younger sequence, that may be evidence that the Yerington batholith is exposed at a relatively shallow level in the Wassuk Range.

New mapping (plotting and interpretation in progress) indicates lithologies in the volcanic rocks west of the Ludwig Limestone that appear to be different from those usually seen in the Triassic section, and that more closely resemble Jurassic rocks. This section of volcanic rocks appears to overlie and truncate the major fault to the east that places the Ludwig Limestone and Gardnerville Formation of the Northern Lights Mine against Triassic volcanic rocks to the north. No evidence was found for a major fault contact between Ludwig Limestone and the volcanic rocks west of it. On the west side of these volcanic rocks (pre-tilt above them) a breccia of uncertain origin was found, unlike any unit found previously in the Triassic or Jurassic section. While further work is needed, preliminary results suggest that the volcanic rocks west of the Ludwig Limestone could be a section separate from the Triassic to earliest Jurassic section, and could be a Middle Jurassic, or possible even younger unit.

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