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11. MYRMEKITE IN GARNET-SILLIMANITE-CORDIERITE GNEISSES AND Al-Ti-Zr TRENDS, GOLD BUTTE, NEVADA

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Introduction

This presentation illustrates how myrmekite can be a clue that some garnetiferous gneisses are derived from deformed mafic igneous rocks rather than from metamorphism of pelites. The terrane that supports this hypothesis is the Gold Butte area in southeastern Nevada (Fryxell et al., 1992; Volborth, 1962). See inset, Fig. 1.

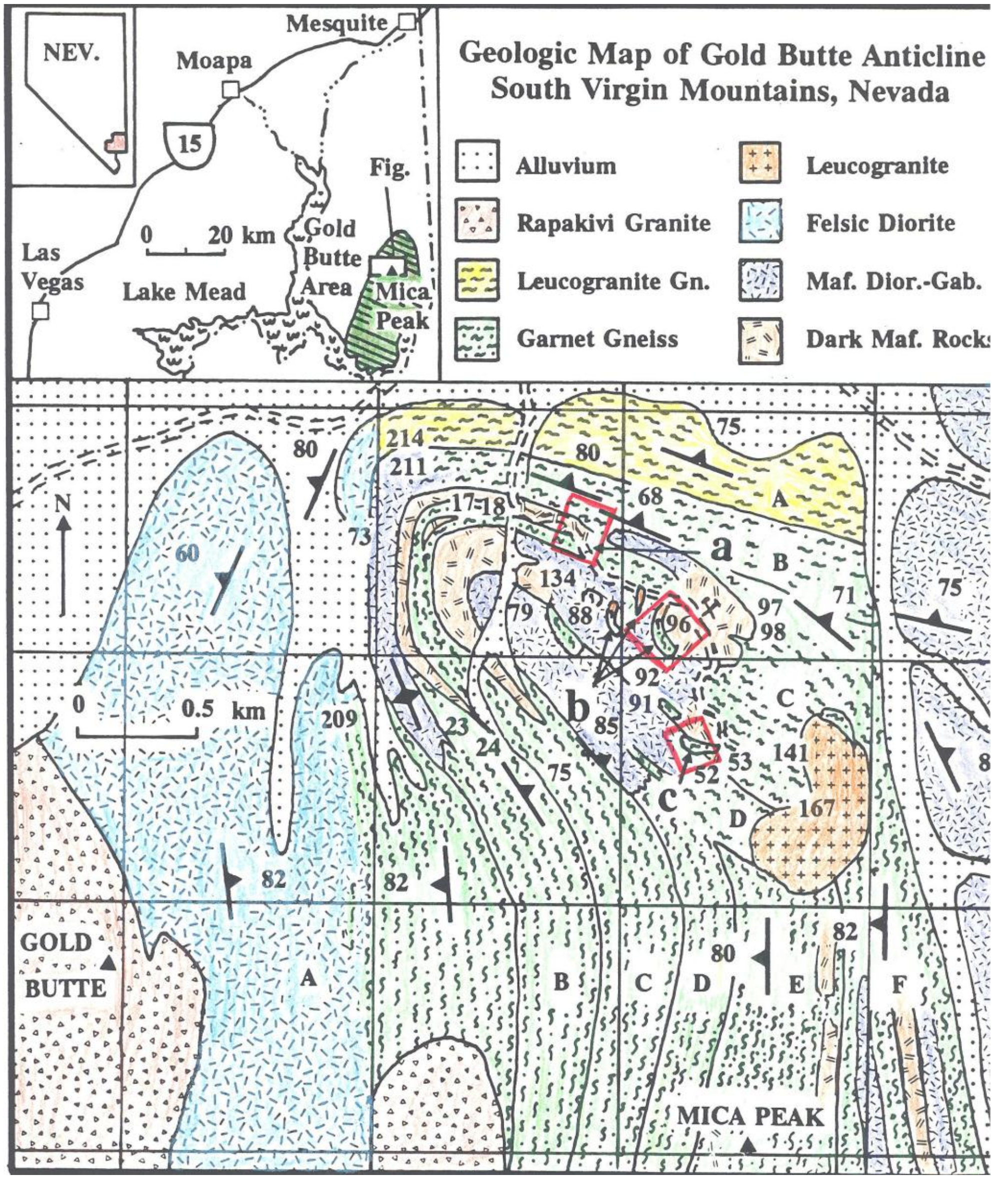

Fig. 1. Location of Precambrian Gold Butte area, Nevada, and geologic map of Gold Butte anticline. Mine symbol locates vermiculite mine. Grid pattern from Gold Butte 7 1/2 Minute Quadrangle, Nevada, is 1 km on a side. Symbols A-F refer to units in Fig. 2. Sites a, b, and c (outlined in red boxes) are illustration locations on Fig. 4. Garnet gneiss includes gneisses that may also contain sillimanite +/- cordierite. Symbol for dark mafic rocks (paired-line patterns) include mafic diorite, gabbro, mafic gabbro, and pyroxenites that have abundant mafic silicates. Twenty analyzed rocks are approximately located by sample numbers, but tables of analyses have been omitted from this web site.

In this terrane a nearly-isoclinal, steeply-plunging anticline northeast of Gold Butte and north of Mica Peak (insets and main map in Fig. 1. Fryxell et al. (1992) and Volborth (1962) suggested that mafic and ultramafic igneous rocks were younger and intruded as phacoliths into older garnetiferous gneisses, which they considered to be metapelites. Remapping of this same anticline in greater detail (Fig. 1; main map) and detailed studies of thin sections show that the igneous rocks are actually older than the garnetiferous gneisses. The following discussions [provide the evidence to support this conclusion.

Geologic setting

The mafic igneous layers in this anticline maintain constant thickness over the nose of the fold, uncommon in phacolithic intrusions. In deformed zones in the limbs of the fold, igneous layers become thinner (Fig. 1). The igneous rocks do *not* cross-cut the gneisses, as portrayed in maps prepared by Fryxell et al. (1992) and Volborth (1962). Instead, the igneous layers have sharp, parallel, non-cross-cutting contacts with adjacent gneisses, extending from one limb through the nose to the opposite limb. The igneous rocks do *not* contain enclaves of the gneisses nor do any tiny dikes extend into the adjacent gneisses. Instead, locally, the *gneisses contain fragments of the igneous rocks*. In addition, at the base of the fold, the garnetiferous gneisses *cut across the igneous layers*. In the fold, along strike, the igneous rock layers *feather and grade into the gneisses*. The feathering may occur within a few meters or for a few hundred meters. For example, between the granite gneiss and the felsic diorite, long narrow stringers of the gneiss (1 m wide) in the northeast limb extend around the nose of the fold into the diorite on the northwest limb for 200 m where they gradually thin and disappear (Fig. 1). Similarly, thin felsic diorite layers extend into the gneiss in the northeast limb before disappearing.

A schematic interpretation of the isoclinal fold is shown in Fig. 2.

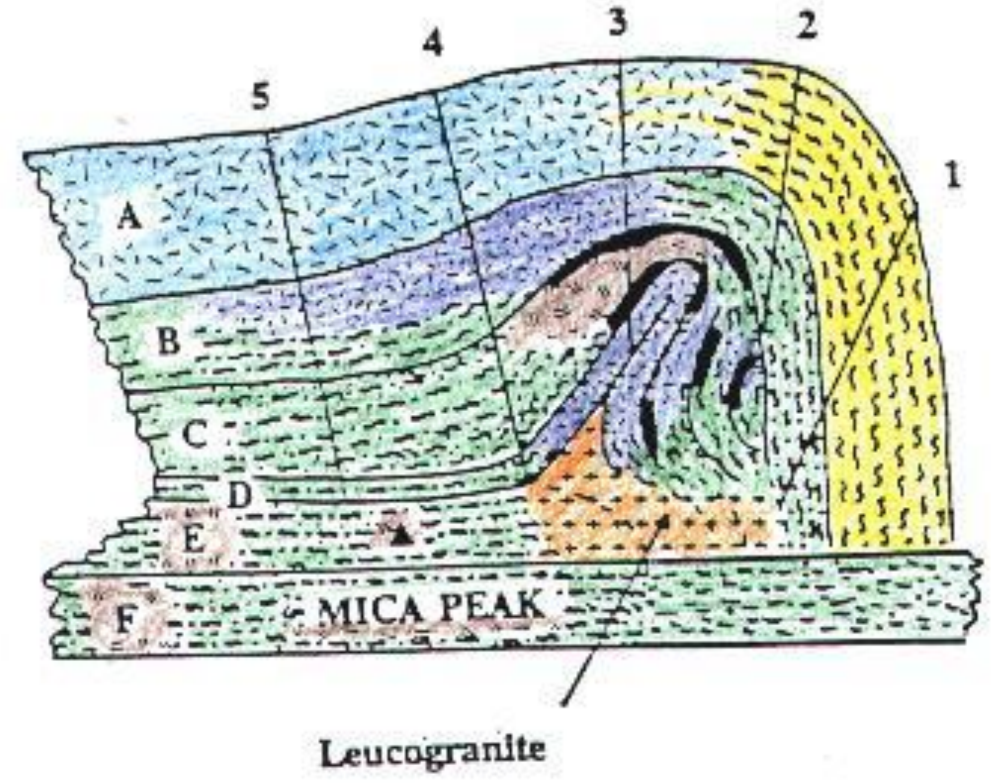

Fig. 2. An interpretive diagram, showing relative positions of units A-F in the Gold Butte anticline; not at the same scale as in Fig. 1. A = felsic diorite; B and D = mafic diorite; C = mafic diorite, gabbro, mafic gabbro, and ultramafic rocks (black areas indicate two layers rich in mafic silicates); E and F = mafic diorite, gabbro, and mafic gabbro.

Rock types and thin section analyses

The igneous rocks are varied, consisting of felsic (sodic) diorite, mafic (calcic) diorite, (sodic) gabbro, mafic (calcic) gabbro, and ultramafic rocks (Fig. 3). Orthopyroxene occurs throughout these rocks, and coexisting biotite and hornblende are common. Clinopyroxene also occurs but is rare. The orthopyroxene compositions range from magnesium-rich species (less than Fs_{20}) to iron-rich species (near Fs_{70}), but most ultramafic rocks contain magnesium-rich orthopyroxene (Fig. 3). Plagioclase compositions range from An_{26} to An_{87}.

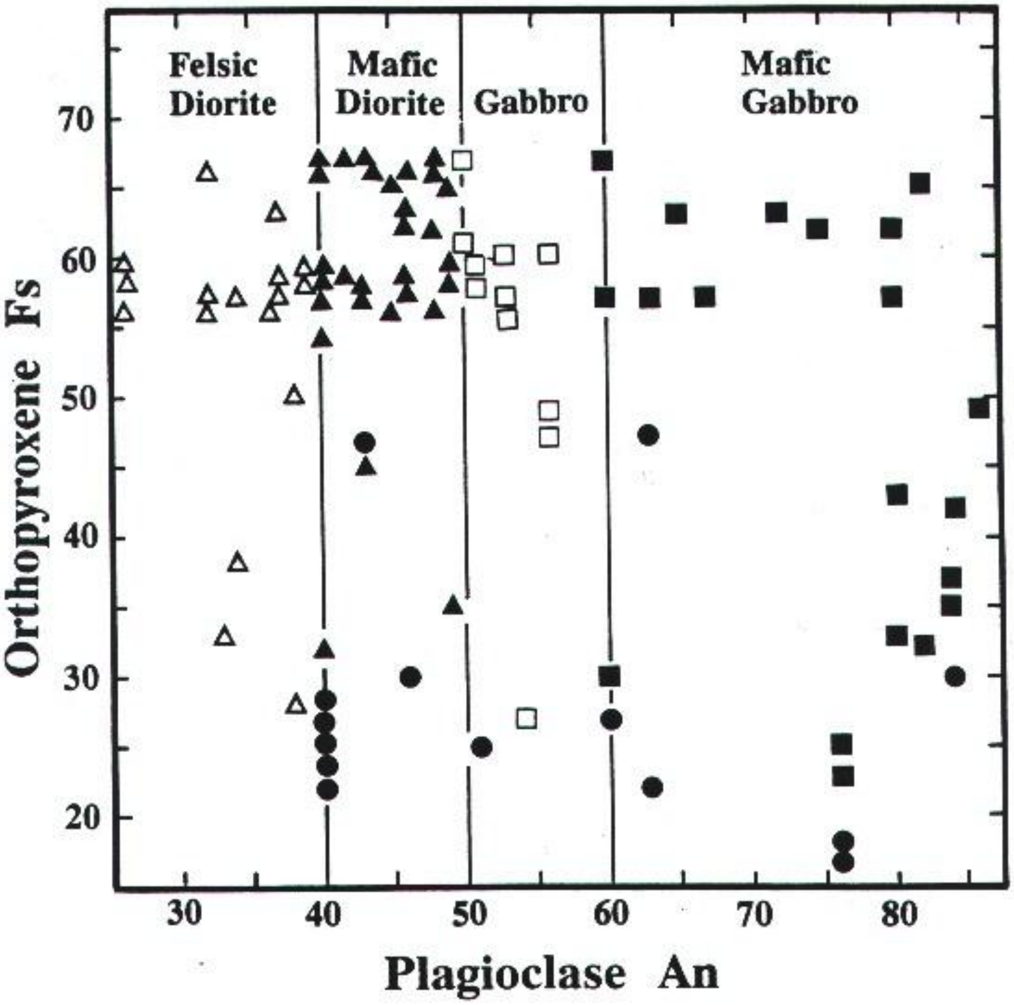

Fig. 3. Ferrosilite (Fs) content of orthopyroxene plotted against anorthite (An) content of plagioclase in igneous rocks of the Gold Butte anticline. Solid circles are ultramafic rocks containing >80 vol% mafic silicates.

The metamorphic rocks consist of granitic gneiss, garnet gneiss, garnet-sillimanite gneiss, and garnet-sillimanite-cordierite gneiss. K-feldspar, sodic plagioclase, quartz, and myrmekite occur in the granite gneiss, garnet-gneiss, and garnet-sillimanite gneisses, but myrmekite is generally absent in garnet-sillimanite-cordierite gneisses.

Thin section analyses of igneous rocks, gneisses, and transition zones where igneous rocks feather into the garnetiferous gneisses, show variation in mineralogy, chemical compositions, textures, and modal compositions.

1. *Mineralogical, chemical, and textural correlations*.

In the transition zones where the igneous rocks grade into gneisses, there is a significant correlation between *types of igneous rocks and kinds of gneisses* they grade into. Felsic (sodic) diorite grades into granite gneiss lacking garnet. Mafic (calcic) diorite grades into garnet gneiss (Fig. 4); mafic (very calcic) diorite and (sodic) gabbro grades into garnet-sillimanite gneiss; and mafic (calcic) gabbro grades into garnet-sillimanite-cordierite gneiss. Also, in the transition zones, orthopyroxene gradually disappears as modal quartz percentages of quartz increase. Hornblende and biotite also gradually disappear, but these minerals may have quartz sieve textures before hornblende totally disappears. Some biotite is present in the gneisses. Deformed plagioclase crystals in the transition rocks contain interior K-feldspar *and are antiperthitic*. Where K-feldspar is first seen as isolated grains, myrmekite may also be found on their borders. First appearances of garnet in a transition zone commonly occur in narrow stringers (less than 0.5 c wide) where adjacent stringers of the igneous rocks still have remnant orthopyroxene.

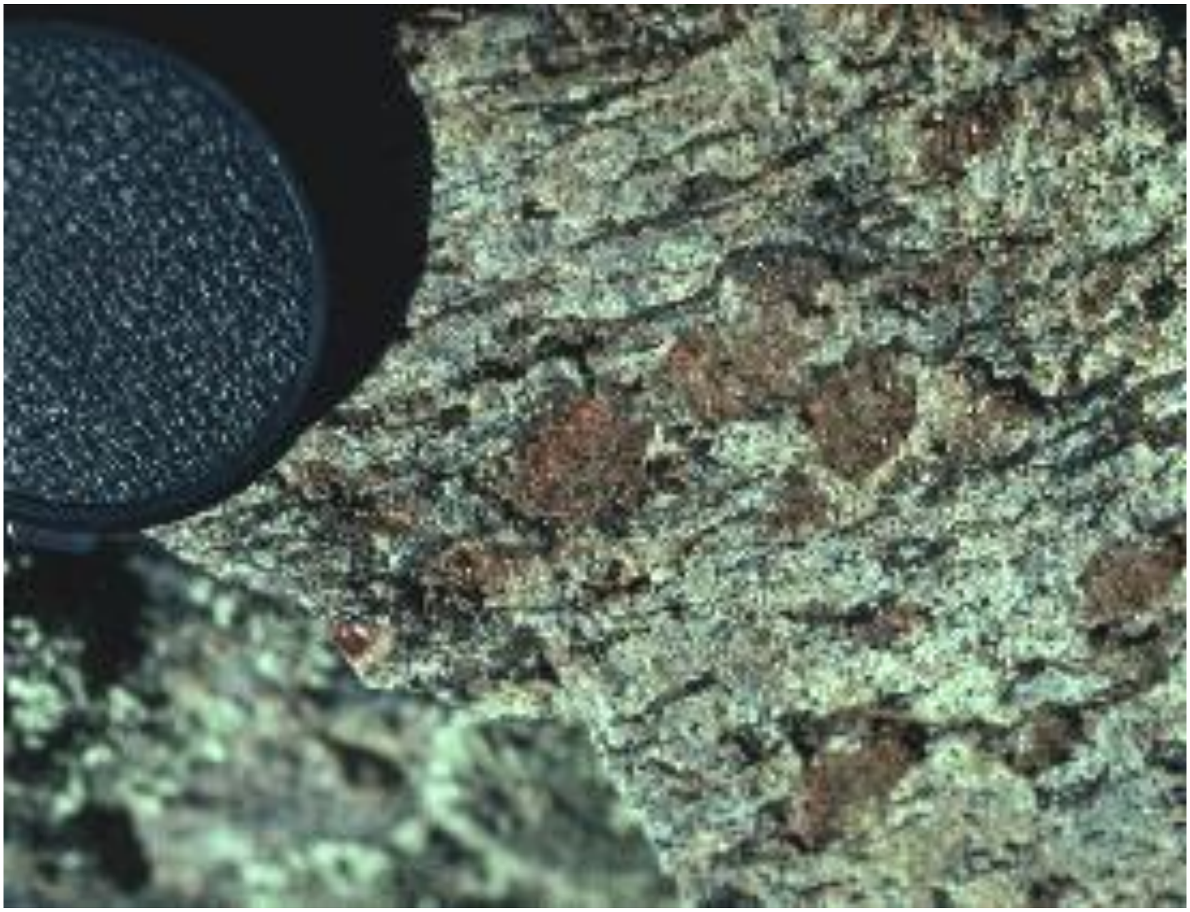

Fig. 4. Photo of garnet gneiss (lens cap for scale).

In these transition zones, a direct correlation exists between plagioclase compositions (An content) in the igneous rocks and sizes of quartz vermicules in myrmekite. That is, where diorite is sodic and felsic with plagioclase (An_{22-35}), the transition zone has only small amounts of myrmekite with tiny quartz vermicules (Fig. 5). Where the diorite is more mafic and calcic, containing plagioclase (An_{35-45}, the quartz vermicules in myrmekite are intermediate in size. Where the protolith is a very calcic diorite, sodic gabbro, or a mafic calcic gabbro, containing plagioclase (An_{45-87}), quartz vermicules in myrmekite are coarse (Fig. 6).

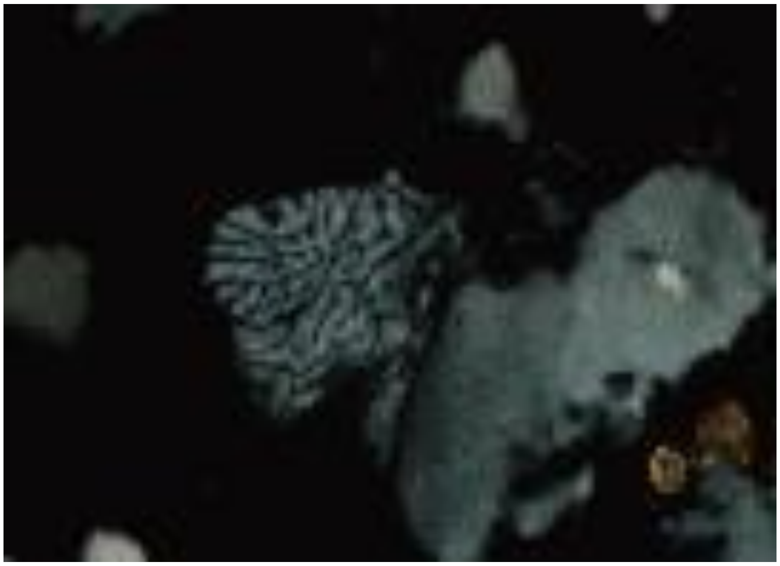

Fig. 5. Myrmekite with tiny quartz vermicules in sodic diorite containing biotite, plagioclase (An_{34}) and orthopyroxene (Fs_{57}).

Fig. 6. Myrmekite with coarse quartz vermicules in biotite-orthopyroxene, calcic, mafic gabbro in transition to garnet-sillimanite gneiss along strike in the Gold Butte terrane. Plagioclase composition is An_{80}; orthopyroxene composition is Fs_{57}.

Extending beyond the transition rocks into the gneisses, the above correlation no longer exists. The quartz vermicules in myrmekite in the garnet and garnet-sillimanite gneisses *are tiny* (Fig. 7) *and do not correlate* with plagioclase compositions in the igneous rocks along strike. Moreover, generally no myrmekite occurs in garnet-sillimanite-cordierite gneisses. In these same garnetiferous gneisses the associated plagioclase is oligoclase (An_{22-27}).

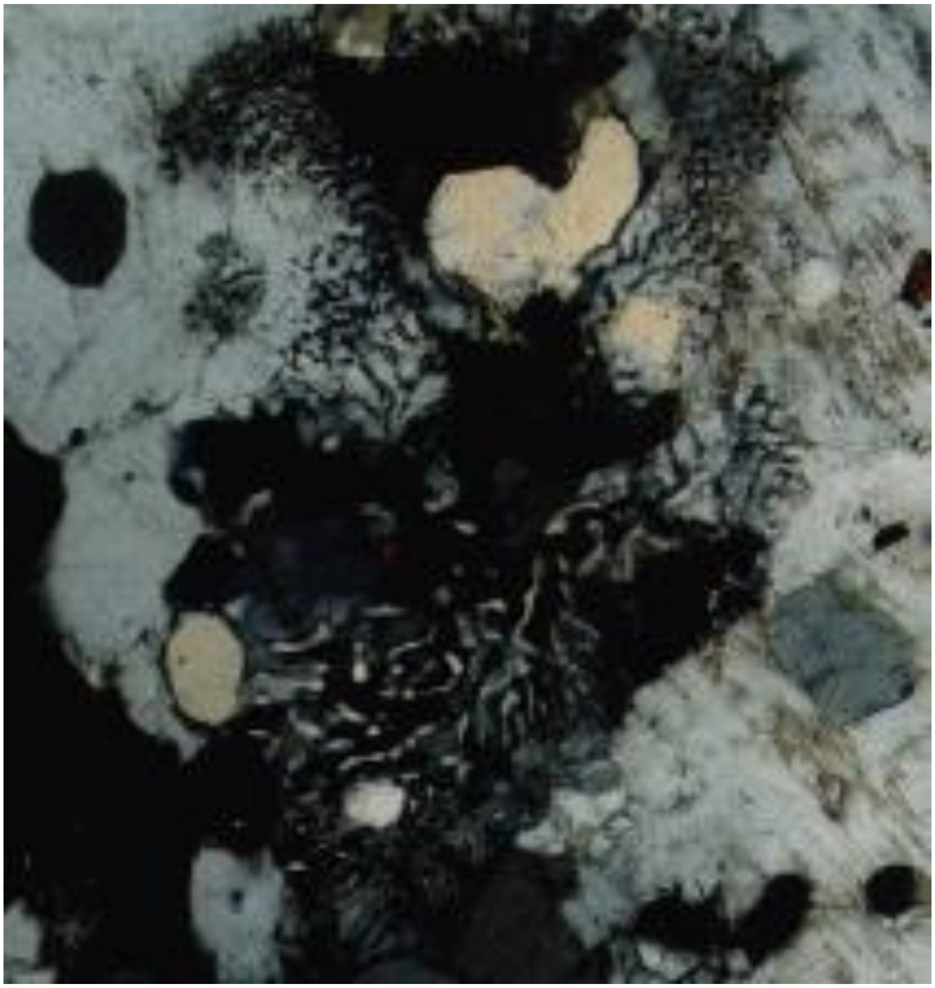

Fig. 7. Myrmekite with tiny quartz vermicules and occurring between two K-feldspar crystals in garnet-sillimanite gneiss. Plagioclase modal composition is 28 vol%. Former igneous rock along strike is a calcic, iron-rich, mafic gabbro.

2. *Modal compositions*.

Plagioclase modal compositions start from high values in the mafic igneous rocks and drop to low values as K-feldspar increases gradually in the deformed igneous rocks toward the various gneisses. Similarly, modal compositions of pyroxenes, hornblende, and biotite have relatively high values in the mafic igneous rocks, and these ferromagnesian silicates gradually disappear as quartz increases in the deformed rocks and completely disappear (except for small percentages of biotite) where garnet, sillimanite and/or cordierite are present in the gneisses.

Deformation and mineral relationships in various structures

1. *Deformation*.

Because of strong forces pushing on rocks in the northeastern limb producing the tight anticlinal fold, adjacent layers on the limbs of the fold must have been subjected to considerable movement parallel to one another. Relative amounts of sliding are indicated by shifts in the positions of equal-spaced reference lines, 1 through 5, that were once perpendicular to the layers prior to folding (Fig. 2). The sliding and deformation would have produced the foliation that occurs in the gneisses and transition rocks.

2. *Examples of mineralogical and modal changes that are related to structure*.

Structures that illustrate the kinds of mineralogical transitions from igneous rocks to the gneisses are shown in Fig. 8. Their locations are shown in Fig. 1.

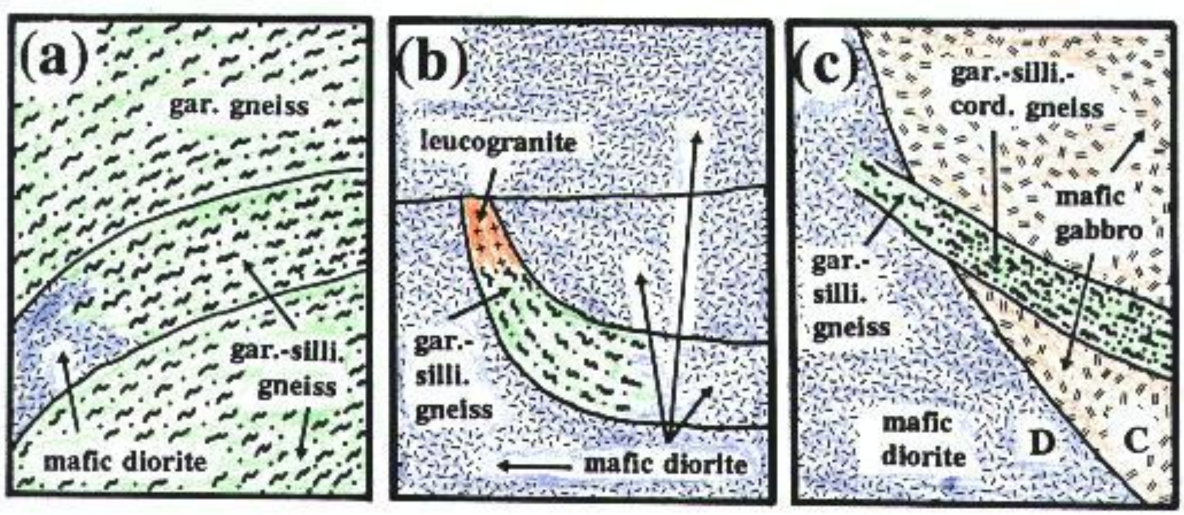

Fig. 8. Schematic diagrams of structural relationships in igneous rocks and garnetiferous gneisses. Locations of a, b, and c are outlined in red-lined squares on Fig. 1.

In Fig. 8 (a), mafic diorite (blue) is shown to grade and feather into garnet-sillimanite gneiss (green) along strike of the layer, but has sharp contacts agains garnet-bearing gneisses along its sides.

In Fig. 8 (b), garnet-sillimanite gneiss is bounded by mafic diorite and grades into it along strike of the foliation in the diorite (blue). As the foliation bends to an acute or perpendicular angle abutting mafic diorite at the opposite end, the garnet-sillimanite gneiss *grades to leucogranite* (orange) (Fig. 9) and becomes less thick.

Fig. 9. Felsic fine-grained leucogranite with tiny garnets. Lens cap for scale.

In Fig. 8 (c), where the gneiss cuts across the igneous layers, where it is bordered by mafic gabbro (brown), it is a garnet-sillimanite-gneiss, but where this gneiss extends into the adjacent mafic diorite (blue), the gneiss contains only garnet and traces of sillimanite.

Interpretations

On the basis that the granite and garnetiferous gneisses grade into the igneous rocks along strike and in places even cut across contacts between different kinds of igneous rocks, a phacolithic model seems unlikely. In addition there are no evidences for assimilation in the igneous rocks or any contact reactions in the gneisses which might be expected adjacent to granitic gneisses where melting and mixing could occur. Furthermore, fragments of igneous rocks in gneiss would not be expected in a phacolith model. The continuous deformation and cataclasis of crystals, caused by folding and resultant sliding of adjacent layers in the limbs, could have created an open system through which fluids could move and cause the observed mineral and compositional changes. For example, in the transition of felsic diorite to granite gneiss, the plagioclase of the felsic diorite is reduced gradually from an average of 62 vol. % to an average of 9 vol. %. At the same time gradual appearance of K-feldspar occurs. The maximum amount of K-feldspar (average, 53 vol. %) is found where stresses are greatest, as in the northeast limb where strong lateral shearing occurred (Fig. 1 and Fig. 2). Introduction of fluids could have caused replacement of plagioclase by K-feldspar with subsequent loss of Ca.

In other more mafic igneous rocks closer to the core of the fold, deformation is also intense, particularly in the northeast limb (Fig. 1). In these mafic igneous rocks, because of the greater abundance of ferromagnesian silicates, smaller volumes of plagioclase occur, and they are more calcic and aluminous than in plagioclase in the felsic diorite. When these more mafic igneous rocks are deformed and gradually replaced, Ca also leaves the system, but excess Al could have been transferred with released Fe and Mg to form garnet, cordierite, or sillimanite. Any remnant recrystallized plagioclase is quite sodic (An_{22-27}, reduced in volume, and relatively poor in Al. In the garnet-sillimanite-cordierite gneisses, so much Ca is lost and so much Al is transferred to the aluminous minerals in the gneisses that K-replacement of plagioclase is generally complete, and in most places no myrmekite is formed. What little plagioclase remains, ranges from zero to 7 vol. %, averaging 3 vol. %.

Where the garnet-sillimanite-cordierite gneiss (Fig. 1 c and Fig. 8 c) extends through a Mg-rich mafic gabbro layer and then abruptly changes to garnet-sillimanite gneiss as the gneiss extends for a short distance into an adjacent Fe-rich mafic diorite, there is no apparent offset of the two igneous rock types. On that basis, the shear zone, which permitted the garnetiferous gneisses to form by metasomatism, is interpreted to be a scissors-type movement which dies out into the mafic diorite. In any case, *such an abrupt change in gneiss type across an igneous contact would be highly unlikely if these gneisses were contact-metamorphosed pelites*.

Where a layer of garnet gneisses extends from one limb of the fold to the other with parallel contacts with adjacent mafic igneous layers Fig. 1, there are no remnants along strike of the igneous rock that would be a clue for the kind of mafic igneous rock that is interpreted to have once been there. This continuous layer eventually joins up with other layers of gneiss when the adjacent mafic igneous rocks disappear along strike. The only clue to its origin is that these gneisses are like the garnet gneisses which show a direct transition to mafic diorite in other layers. On this basis, a mafic diorite, perhaps rich in biotite, is interpreted to have existed here at one time. Biotite is easily cleavable so that if this mafic diorite were biotite-rich, it could have been readily deformed and totally replaced by garnet gneiss. In contrast the adjacent mafic and ultramafic rocks that contain little biotite and abundant hornblende and orthopyroxene would tend to be preserved and unreplaced because they are stronger and less easily sheared (Fig. 10). *In such a situation replacements of the biotite-rich mafic diorites would be parallel to the contact with mafic, biotite-poor, igneous layers and not at right angles to it*.

Fig. 10. Preserved mafic (calcic) diorite containing abundant hornblende and orthopyroxene and only minor percentages of biotite.

If the igneous rocks were replaced by the garnet gneisses, what gains and losses could have occurred? The following example illustrates possible elemental gains and losses between a mafic gabbro and adjacent garnet-sillimanite-cordierite gneiss along strike. The gains are K, Na, Al, Ba, Zr, and Rb, and the losses are Ca, Mg, Fe, Mn, Ti, Zn, P, and Sr. This conclusion is obtained by plotting elements and oxides in an isocon diagram (Fig. 11) in which element movements are compared relative to constant volume or constant mass (after Grant, 1986). During the conversion, SiO_2 seems to remain nearly constant for the whole rock, if the volume remains constant.

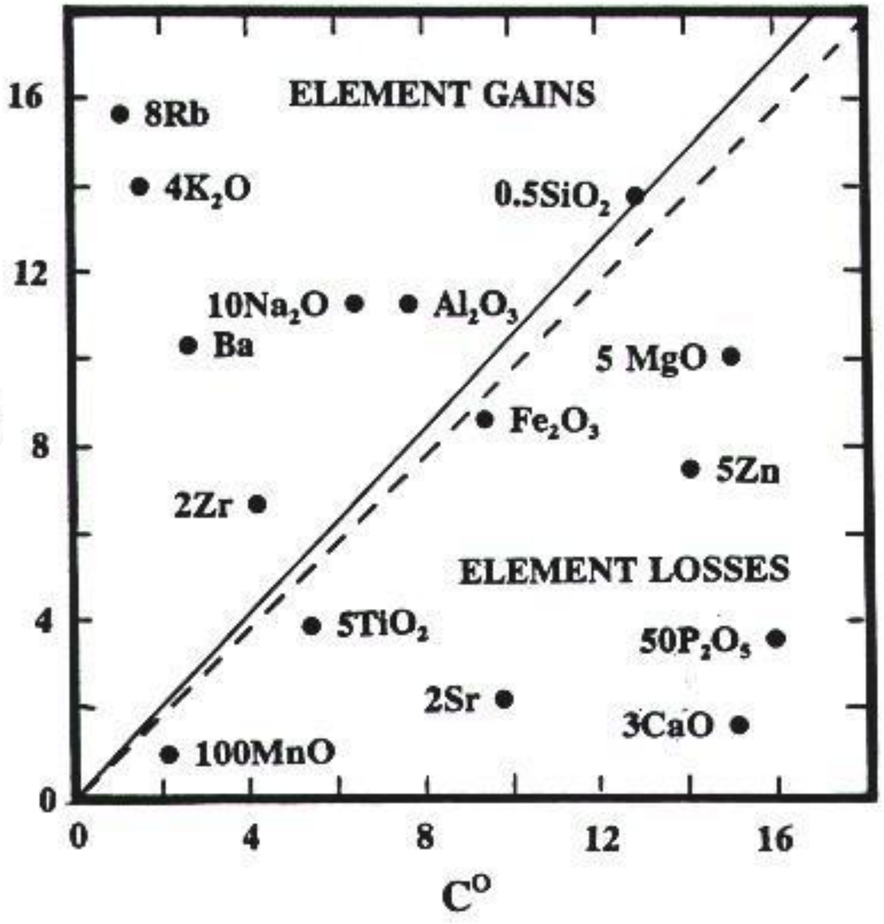

Fig. 11. Original element concentrations C^O in mafic gabbro protoliths in comparison to altered element concentrations C^A in replaced rocks that are now garnet-sillimanite-cordierite gneisses (after Grant, 1986). Major oxide abundances

are in wt%; trace elements are in ppm. Some values are proportionally scaled. Solid line = constant volume reference frame; short-dashed line = constant mass reference frame. Elements plotting to the left of any reference isocon represent gains; those to the right represent losses. Data points should be connected with a line to the origin (zero point). What is significant for the scaled values is not the distance of the data points from the lines representing constant mass or constant volume nor the distance from the origin but the angles or deviations of the lines to the data points relative to the central dashed or solid lines.

Discussion

1. *Garnetiferous gneisses --- meta-igneous or metapelites?*

Fryxell et al. (1992) and Volborth (1962) assumed that the garnetiferous gneisses were metapelites and older than the igneous rocks which were supposed to have been intrusive phacoliths between layers in the nose of the fold. The heat from these magmatic intrusions was supposed to have aided in the metamorphism of the former pelites into high-grade gneisses. But the field and thin section studies provide evidence that the gneisses are derived from the igneous rocks. This conclusion is supported by the following: (1) the gradual mineralogical and chemical changes along strike of the foliation in combination with the correlation between igneous rock types and kinds of gneisses along strike and (2) the correlation between maximum coarseness of quartz vermicules in myrmekite in the transition rocks along strike relative to the Ca-content of plagioclase in the adjacent igneous rocks along strike. *There would not be any such correlations if the mafic igneous rocks were younger than the garnetiferous gneisses. How could intruding magmas control their compositions to match that of the gneisses along strike in the limbs of the folds?*

The fact that the garnet gneisses in the Gold Butte terrane are not metapelites is also demonstrated when their Al_2O_3-TiO_2-Zr compositions (hereafter called Al-Ti-Zr) of both the gneisses and their igneous protoliths are plotted in a triangular diagram (Fig. 12).

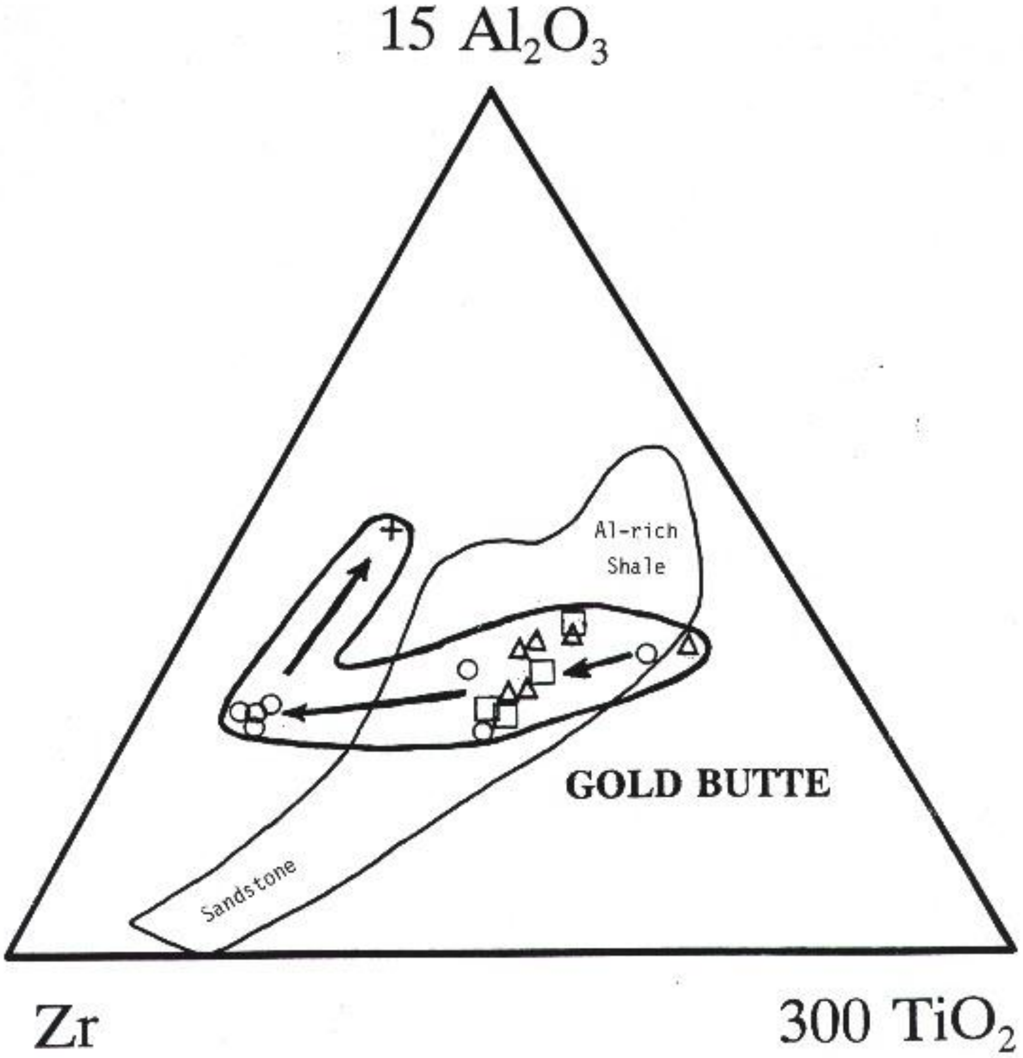

Fig. 12. Example of an Al-Ti-Zr projection of garnet +/- sillimanite +/- cordierite gneisses formed from igneous rocks by metasomatic fractionation form the Gold Butte area of Nevada (Fryxell et al, 1992; Collins, unpublished study). Symbols: granite gneiss = plus; garnet gneiss = open circle; garnet-sillimanite gneiss = open triangle; garnet-sillimanite-cordierite gneiss = open square. Elongate field extending across the gneisses at Gold Butte shows the trend of data points for Al-rich shale at upper right to sandstone at the lower left (Garcia et al. (1994). Figure is from Collins (in press).

On the basis of world-wide trends, compositions of true metapelites plot within the sandstone-shale continuum and have trends parallel to it (Garcia et al., 1991, 1994; Collins, 1996; Shaw, 1956; Munksgaard, 1988). The garnetiferous gneisses in the Gold Butte anticline, however, *project through this continuum at an acute angle* towards the Al-Zr side (Fig. 12) before extending toward the Al corner where granite gneiss plots.

2. *Anatexis*.

Thermobarometry measurements suggest that the garnet-bearing gneisses have equilibrium temperatures of 690-770 º C at a pressure of 320 MPa (reported by Fryxell et al., 1992, but measurements were obtained by other investigators). These temperatures are certainly above the melting interval for granite and suggest that if metasomatic hydrous fluids moved through the deformed igneous rocks at these temperatures, anatexis should have taken place. But if melting had occurred, then myrmekite should not be present in transition rocks nor in the adjacent gneisses. Melting and recrystallization could produce quartz-plagioclase intergrowths, such as granophyric and graphic granite, or perhaps symplectic textures, but the feldspar, enclosing the quartz and crystallizing from such small melt-volumes, should have a uniform composition. The presence of myrmekite in these rocks in which the host plagioclase for the quartz has a gradational composition is enigmatic if anatexis occurred. More experimental work needs to be done, perhaps using hydrogen or carbon dioxide as the means of transporting elements.

3. *Leucogranite*.

The large leucogranite mass at the base of the axial plane of the fold is enigmatic (Fig. 1 and Fig. 2; colored orange). Whether this leucogranite is formed by injection of local anatectic solutions (melts) or whether it is a recrystallized felsic residue that remained after mafic components were removed in hydrous solutions is problematic. But, perhaps it is a combination of both injection of granitic solutions (melts) and replacement (1) because the leucogranite occurs in a relatively low pressure site where anatectic solutions (melts) could migrate and (2) because the leucogranite (a) contains myrmekite, (b) occurs in a position where former igneous rocks would have been subjected to the most granulation and replacement, and (c) is gradational into gneisses and then into the mafic igneous rocks, as is also illustrated in (Fig. 1 b and Fig. 8 b).

4. *Antiperthite*.

The existence of antiperthite in the transition zones could be argued to be a common presence in high-grade metamorphic rocks. In that case, these textures could be explained as being the result of slow cooling accompanied first by expulsion of K from the margins of a plagioclase grain and later by exsolution of K-feldspar in the core of the grain where the original high-K composition is still retained. But in such common occurrences, myrmekite is not found, and the host meta-igneous rocks have not been deformed by lateral sliding. *If the antiperthite textures were formed in the Gold Butte area simply by cooling and exsolution, then they should also exist in the undeformed igneous rocks, and they do not*.

5. *Inclusions of igneous rocks versus inclusions of gneisses*.

On the scale of the geologic map (Fig. 1), large islands of garnetiferous gneiss in the midst of the igneous rocks could be interpreted as inclusions in the igneous rocks. But if that were the case, along strike of their foliation, jagged fractures at the ends of the gneiss blocks should occur as evidence that the gneiss blocks were broken loose to be incorporated in the phacolithic intrusions. That is not the case. Instead, small angular fragments of igneous rocks (10 to 20 cm wide) occur enclosed in the gneiss adjacent to the igneous masses, although these occurrences are local and rare. By normal interpretations of field data, this relationship *should indicate that the igneous rocks pre-date the gneisses*.

6. *Field versus experimental studies*.

The model described in this presentation has been proposed on the basis of what is observed in the field and not on the basis of laboratory experiments. Some petrologists might say that the metasomatic model is a classic example of theory driving interpretations. But the same thing can be said for magmatic models when granites are automatically assumed to be formed from melts and for metamorphic models when aluminous gneisses are automatically designated as metapelites. In any case, proponents for whatever model is used to explain the origin of the garnetiferous gneisses in the Gold Butte area have to explain the same data.

Conclusion

Evidence in the Gold Butte area provides support for the hypothesis that K and Si in introduced solutions cause the replacement of plagioclase and ferromagnesian silicates as Ca is carried away. Much of the Fe, Mg and some Al were transferred to aluminous minerals. As a result granitic and garnetiferous gneisses were formed which also may contain sodic plagioclase, myrmekite, quartz, and biotite. These rock transformations should not be surprising because the felsic and aluminous minerals in the metasomatic high-grade gneisses are stable at temperatures below the solidus for these mafic igneous rocks, whereas such high-temperature minerals as the pyroxenes in the igneous rocks are not. An example of similar conversions of deformed igneous rocks to aluminous gneisses is reported by Collins and Davis (1992).

The possible existence of K- and Si-bearing fluids that could initiate the metasomatism of mafic igneous rocks in the Gold Butte terrane is recently hinted at by the experimental studies made by Wilkinson et al. (1996). These authors show that Si-rich and K-bearing fluids can exist at low temperatures (less than 300º C to more than 750º C) and both high (greater than 1500 MPa) and low pressures (less than 200 MPa).

Attempts to confirm the older age for the mafic igneous rocks relative to the younger age for the garnetiferous gneisses by Rb-Sr age-dating methods were tried but must be considered to be unsuccessful. "Errorchrons" give support to this hypothesis, but the Rb-Sr systematics are disrupted by the openness of the system, and this age dating cannot be fully trusted. Determining age relationships by U-Pb measurements on zircon populations has not yet been attempted.

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