Stable Isotope Geochemistry: A Tribute to Samuel Epstein
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Application of stable isotopes in identifying a major Hercynian synplutonic rift zone and its associated meteoric-hydrothermal activity, southern Schwarzwald, Germany*

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Abstract—Whole-rock and mineral $\delta^{18}O$ analyses were obtained on granites, gneisses, migmatites, and a variety of metamorphosed sedimentary and volcanic rocks from the Schwarzwald massif, focusing on Variscan-age (270–360 Ma) igneous, metamorphic, and hydrothermal events. The data display some remarkable geographical and temporal systematics; the extremely ^{18}O-depleted samples ($\delta^{18}O < +3$) occur only in the southern Schwarzwald, confined to a 3–6 km wide, 50 km long, E–W zone of down-dropped Upper Devonian-Lower Carboniferous sediments and volcanics sandwiched between older, high-grade gneisses on the north and south. This belt of rocks, the Badenweiler-Lenzkirch (B-L) tectonic line, was intruded all along its length by the 1–2 km wide Rand Granite pluton, which also exhibits extremely low $\delta^{18}O$ values. The data imply that a very large meteoric-hydrothermal system was established here within a rift-zone setting, in Late Visean time ($\approx$340 Ma). This date is fixed by paleontological evidence indicating that the B-L zone sediments changed from marine to terrestrial at this time, because the meteoric-hydrothermal event documented by the $^{18}O/^{16}O$ data obviously could not have occurred while marine sedimentation was taking place. The δD values of biotite, hornblende, and chlorite in 31 migmatite, schist, and gneiss samples from the B-L zone range from −60 to −111, but the most ^{18}O-depleted of these samples ($\delta^{18}O < +4$) all have $\delta D < -90$. Assuming that these rocks were altered by hydrothermal fluids that originally had $\delta^{18}O$ and δD on the Meteoric Water Line, we calculate that the ground waters in this area had $\delta^{18}O \approx -6$ to -9 and $\delta D \approx -40$ to -65 at that time, compatible with geological data suggesting a low latitude and sub-tropical climate. Previous geological models of the B-L zone emphasize collisional tectonics and conclude that it is a thrust-zone; however, such models are not compatible with the $^{18}O/^{16}O$ data. Our preferred model invokes formation of a dilatant zone along a major strike-slip fault at about 340 Ma. This pull-apart was intruded by the Rand Granite, which acted as the main "heat engine" that drove this large convective system. As the hydrothermal activity weakened, the B-L zone continued to deform, and the solidified pluton was stretched out and strongly attenuated. The hydrothermal episode and the strike-slip deformation both terminated prior to intrusion of some large, post-tectonic, two-mica granite plutons (which truncated the B-L zone and Rand Granite at about 300–315 Ma); these late plutons are not hydrothermally altered or ^{18}O depleted. This work suggests that in complex geological terranes stable isotope data may be one of the best ways to identify fossil synplutonic rifts or pull-aparts associated with major strike-slip faults.

INTRODUCTION

IN THIS PAPER we discuss $^{18}O/^{16}O$ and D/H relationships of the igneous and metamorphic rocks of the southern Schwarzwald (Black Forest), particularly focusing on the area from Badenweiler and Freiburg, eastward to Lenzkirch (Fig. 1). The study area is an uplifted block of Hercynian (=Variscan) and pre-Hercynian crystalline basement rocks on the eastern side of the Rhine Graben (Fig. 1). An analogous basement uplift occurs to the west of the Rhine, forming the Vosges Mountains in France.

Previous stable isotope studies of the Schwarzwald massif are those of MAGARITZ and TAYLOR (1981), HOEFS and EMMERMANN (1983), and SIMON and HOEFS (1987). The present study builds upon, and is an outgrowth of, these earlier studies. The original study by MAGARITZ and TAYLOR (1981) was undertaken specifically to examine the $^{18}O/^{16}O$ and D/H relationships in granite migmatites, in the hope that such studies might provide added information about the genesis of such rocks and about the general problem of anatexis of the continental crust. The localities chosen for that stable isotope study by MAGARITZ and TAYLOR (1981) were some of the classic migmatite outcrops described by MEHNERT (1968); the sampling was carried out specifically with the migmatite problem in mind, with the guidance and assistance of W. Wimmenauer. At each migmatite outcrop, samples were taken from coexisting leucosome-melanosome

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pairs (the leucosome being the medium- to coarse-grained, granitic portion of the migmatite and the melanosome being the biotite-rich, finer-grained, more mafic portion). Several of the most interesting of these migmatite exposures are found adjacent to, and within, an east-trending, elongate zone of strongly foliated granitic rocks and Upper Paleozoic sediments and volcanics that extends about 50 km eastward from Badenweiler. This zone (shown in black on Fig. 1) is referred to in the literature as the Badenweiler-Lenzkirch zone or tectonic line; in this paper, we commonly abbreviate it either as B-L zone or B-L line.

MAGARITZ and TAYLOR (1981) also carried out a variety of regional isotope studies of the Hercynian granites and older gneisses throughout the area of the southern Schwarzwald, extending these studies southward almost to Basel, Switzerland. Similar reconnaissance stable isotope studies were carried out by HOEFS and EMMERMANN (1983) and SIMON and HOEFS (1987), and these latter studies also extended much farther north, encompassing the entire Schwarzwald massif. Each of the above studies discovered some systematic relationships in the Hercynian igneous and metamorphic rocks of the Schwarzwald that were generally similar to relationships established elsewhere in the Hercynian of Western Europe, for example in the Pyrenees by MICHARD-VITRAC *et al.* (1980), in Brittany by ALBARÈDE *et al.* (1980), in Cornwall by SHEPPARD (1977), and also to relationships established subsequently in the Pyrenees by WICKHAM and TAYLOR (1985, 1987). We will not review these previous studies here, as they have been discussed in some detail by SHEPPARD (1986a), who also reviewed data from the Massif Central. We simply note the following: (1) Many of the granitic plutons emplaced *during* these Pan-European Variscan orogenic and metamorphic events are cordierite-, biotite-, or muscovite-bearing, peraluminous, S-type granites with relatively high $\delta^{18}O$ values of +11 to +12. (2) Other Variscan granitic rocks, particularly those emplaced after the peak of metamorphism, are typically calcalkaline and have lower $\delta^{18}O$ values, usually about +9 to +10.

In striking contrast to the Hercynian localities mentioned above, a unique feature was discovered in the $^{18}O/^{16}O$ studies of the southern Schwarzwald that clearly implied the existence of a Hercynian meteoric-hydrothermal metamorphic event of some type. MARGARITZ and TAYLOR (1981) found a few isolated samples with unusually low $\delta^{18}O$ values, particularly in some of the granitic plutons, and similar effects were also observed by HOEFS and EMMERMANN (1983). More significantly, however, MAGARITZ and TAYLOR (1981) found that many

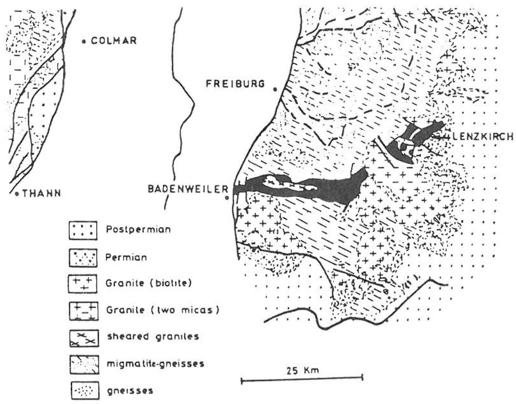

FIG. 1. Generalized geologic map of the southern Schwarzwald, Germany (on the right) and the easternmost Vosges, France (on the left); these two Hercynian (Variscan) terranes are separated by the Rhine graben. The elongate, east-trending, solid black area in the Schwarzwald is the Badenweiler-Lenzkirch (B-L) zone interpreted as a north-dipping thrust zone by FLUCK *et al.* (1980), but which we are interpreting as a rift zone or pull-apart, based upon characteristic $\delta^{18}O$ values lower than +4 (see text). The elongate granite body in the western part of the B-L rift zone is the Münsterhalden Granite. The later-stage Hercynian granites that truncate the low-^{18}O B-L zone southwest of Lenzkirch are the Bärhalde and Schluchsee plutons discussed in the text. Modified after FLUCK *et al.* (1980).

of the samples that they had selected for their migmatite study had unusually low $\delta^{18}O$ values, in the range +1 to +5. This astonishing result was totally unexpected, as it seemed to imply that deep circulation of low-^{18}O meteoric groundwaters might be occurring downward into the realm of anatexis and migmatite genesis. In fact, it was this suggestion of MAGARITZ and TAYLOR (1981) that triggered the original studies by WICKHAM and TAYLOR (1985), who searched for similar features in the Pyrenees. Although WICKHAM and TAYLOR (1985) did not find such low-^{18}O meteoric-hydrothermal signatures in the Pyrenees, they did find abundant evidence showing that large quantities of analogous, higher-^{18}O, higher-D aqueous fluids were involved in Hercynian prograde metamorphism; they concluded that those metamorphic-hydrothermal fluids in the Pyrenees were also derived from surface waters, either sea water or marine formation water, based on their distinctive isotopic signatures.

Thus, it appeared that generally similar processes might be occurring in these two widely separated areas of Hercynian metamorphism, except that low-^{18}O meteoric ground waters were clearly involved locally in the Schwarzwald, whereas higher-^{18}O marine formation waters appeared to have been involved in the Pyrenees. Note that it is inherently easier to discern the metamorphic effects of low-^{18}O meteoric-hydrothermal waters than the effects of higher-^{18}O marine waters, because of the much greater isotopic contrast between the former and most crustal rocks. Thus, it seemed likely that a detailed stable isotope comparison between the Hercynian of the Schwarzwald and the Hercynian of the Pyrenees might prove to be very informative. To this end we collected more than 200 new samples during the summer of 1987, and most of these were subsequently analyzed at Caltech. In this interim report we integrate and compare these new isotopic data with the pre-existing data set of MAGARITZ and TAYLOR (1981) and HOEFS and EMMERMANN (1983).

During our field studies in 1987 it became even more apparent to us that it was going to be important to center our new sampling upon the elongate B-L zone that extends eastward from Badenweiler (Fig. 1), which through serendipity had been the focus of the migmatite sampling effort by MAGARITZ and TAYLOR (1981). In particular, we realized that this B-L zone had probably been misinterpreted as a compressional feature in earlier geologic studies, and that it was instead very likely some type of extensional feature, such as a rift-zone or a pull-apart. Thus we re-sampled the B-L zone in detail, and we also extended our new sampling well to the east, along the extension of this zone all the way to Lenzkirch. In addition, in order to provide comparisons with all the new isotopic data obtained along the B-L tectonic line, we also obtained considerable new isotopic data on the older gneisses and migmatites to the north and south, and on the younger Hercynian granite plutons that truncate the B-L zone.

GENERAL GEOLOGICAL RELATIONSHIPS

Regional overview

Variscan and pre-Variscan crystalline basement rocks appear on both sides of the Rhine Graben in two distinct massifs—the Vosges and Black Forest (Fig. 1). Although there are distinct differences between the individual histories of the two massifs, a number of similar sedimentary, volcanic, metamorphic and intrusive sequences can be established on both sides of the Rhine Graben. Below we review the geology in some detail because the main purpose of this paper is to use the evidence of stable isotope geochemistry to propose a new geological model for the evolution of part of the southern Schwarzwald.

Crystalline basement

The basement rocks of the two massifs are mainly of Precambrian age, but could possibly include a range into early Paleozoic ages (HOFMANN, 1979; FLUCK *et al.*, 1980; WIMMENAUER, 1980). They include leucocratic gneisses, amphibolites, kinzigitic gneisses and sillimanite-biotite gneisses with quartzites. These gneisses apparently underwent a widespread anatectic event at about 470 Ma (HOFMANN and KÖHLER, 1973).

In the southern Schwarzwald migmatites are abundant, as are metagreywacke paragneisses (plagioclase-biotite-quartz ± cordierite ± sillimanite) with abundant small amphibolite bodies. At the southern margin of the Schwarzwald massif, leucocratic gneisses and interstratified amphibolites may represent a metavolcanic sequence (silicic tuffs and/or subvolcanics with basaltic interlayers; WIMMENAUER, 1980). Gneisses and migmatites immediately to the north of the B-L zone have yielded ages of about 330–360 Ma (LEUTWEIN and SONET, 1974; KROHE and EISBACHER, 1988; BREWER and LIPPOLT, 1974), which is similar to the age of emplacement of the elongate Rand Granite pluton (see below).

As discussed by EISBACHER *et al.* (1989) and LUSCHEN *et al.* (1987) the Schwarzwald crust is about 25–26 km thick and the refraction Moho ($Vp = 8.2$ km s^{-1}) is remarkably flat. The lower crust is 10–12 km thick ($Vp = 6.7$ km s^{-1}). The upper crust down to a depth of 8 km exhibits an increase in Vp from 5 to 6 km s^{-1} and it contains distinct groupings of dipping reflectors that extend all the way through the upper crust. These reflectors are correlated with the mylonitic shear zones of the Todtnau thrust complex, which crops out at the north edge of the B-L zone (see below).

Low-grade Upper Devonian-Lower Carboniferous sediments and volcanics

Upper Devonian and Lower Carboniferous sedimentary and volcanic rocks of low metamorphic grade (*e.g.*, chlorite, epidote) are found along several of the so-called Hercynian-age tectonic lines that cut the Vosges and Schwarzwald massifs. Although such rocks are fairly common in the southern Vosges, in the entire Schwarzwald massif they are found only along the Badenweiler-Lenzkirch (B-L) line, within a narrow, down-dropped block sandwiched between basement gneisses on the north and a complex gneiss-granite terrane on the south (Fig. 2). According to FLUCK *et al.* (1980), the metamorphism of these rocks occurs close to thrusts and has no stratigraphic significance. Intense mylonitization transforms the sediments as well as the adjacent basement gneisses, producing a prograde effect in the sediments and a retrograde effect in the gneisses (FLUCK *et al.*, 1980).

The B-L zone sediments include greywackes, shales, slates, minor cherts, arkosic sandstones, and conglomerates, and they can be differentiated into two distinct belts that parallel the B-L line (SITTIG, 1981; ALTHERR and MAASS, 1977; MAASS, 1981). In the southern "Schonau" unit, sparsely distributed but stratigraphically distinctive fossils indicate an Upper Devonian to Visean age range (~380–330 Ma, HARLAND *et al.*, 1990). The earliest rocks are marine shales and cherts that must have been deposited in deep water conditions, and these are overlain by more than 1000 m of Lower Carboniferous greywacke and shale, *i.e.* a facies very similar to the Upper Devonian. Some calcareous ooids are found among the greywackes, and subaquatic slides (with pebbles of gneiss) are common. Locally, there are abundant spilites, keratophyres and chert, and the upper parts of the Lower Carboniferous contain reworked ooliths and fossils. Marine sedimentation finally gave way to subaerial conditions, evidenced by the fact that the youngest rocks are terrestrial conglomerates, arkosic sandstones and siltstones, and carbonaceous shales that interfinger with hundreds of meters of lavas and py-

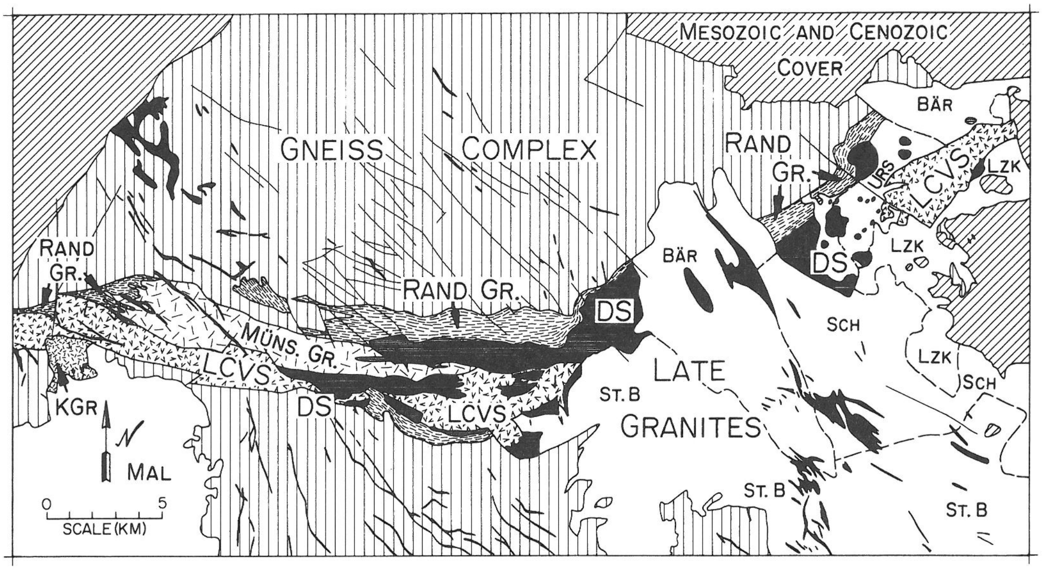

FIG. 2. Generalized geologic map of part of the southern Schwarzwald (modified after METZ and REIN, 1958), showing the principal rock types in the vicinity of the Badenweiler-Lenzkirch (B-L) tectonic line. From generally oldest to youngest, these rock types are: (1) Vertical lined pattern—Basement Gneiss Complex. (2) DS—Upper Devonian-Lower Carboniferous shales and greywacke siltstones and sandstones. (3) LCVS—Lower Carboniferous silicic volcanics, agglomerates, sandstones, and conglomerates, with intercalated crinoidal limestone at one locality. (4) Sub-horizontal dashed pattern—Rand Granite. (5) KGr—Klemmbach Granite. (6) Müns. Gr.—Münsterhalden Granite. (7) Blank pattern—Late Hercynian Granites; this area shown in white contains several plutons of varying ages. In the west, southeast and northeast this area comprises, respectively, the Malsburg (Mal), St. Blasien (St.B), and Lenzkirch (Lzk) granites. In the east, in the vicinity of the gap between the eastern and western parts of the B-L zone, we have the undeformed, very late-stage, post-tectonic granite plutons (Bär—Bärhalde, Urs—Ursee, and Sch—Schluchsee) that definitely truncate the Rand Granite and are clearly much younger than the rocks of the B-L zone. These three plutons are also clearly younger than the aforementioned Late Hercynian granites. (8) The solid black patterns represent latest Hercynian quartz porphyry dikes and hypabyssal plutons of Late Carboniferous to Permian age intruded along a set of pre-existing NW-trending fractures; the age of this brittle deformation has not yet been established, but these conceivably could represent *en echelon* fractures that began to form during pre-Bärhalde strike-slip displacements within the B-L zone (see text). Only a few of these NW-trending fractures are shown on Fig. 2, but they are extremely abundant and pervasive just north of the central B-L zone. (9) Diagonal lined pattern—Mesozoic and Cenozoic cover rocks (*i.e.*, Triassic and younger) that unconformably overlie the Hercynian and pre-Hercynian granites and metamorphic rocks.

roclastic volcanic rocks; the sediments have yielded Late Visean (340–330 Ma) terrestrial plant fossils (BURGATH and MAASS, 1973). In the northern "Geschwend" unit there are large volumes of unfossiliferous sediments that probably span an age range similar to that of the southern unit. The general succession of rock types is similar in both the Vosges and the Schwarzwald, but the sequences in the Badenweiler-Lenzkirch area are much more highly tectonized.

Badenweiler-Lenzkirch (B-L) tectonic line

The Badenweiler-Lenzkirch (B-L) zone is a 3 to 6 km wide, 50-km long, E–W belt of post-Silurian rocks juxtaposed between considerably older basement gneisses; it is just one of a number of such tectonic lines mapped in the Hercynian of Europe. Both the narrow B-L zone and its package of included sediments are completely distinct from the much larger and younger, Upper Carboniferous to Permian, NE-trending, volcano-sedimentary clastic basins that truncate the Schwarzwald to the north and south.

The principal features of the B-L zone are: (1) a down-dropped section of Upper Devonian-Lower Carboniferous metasedimentary and metavolcanic rocks (described above) which forms the southern half of the zone (units DS and LCVS on Figs. 2 and 3); and (2) highly sheared, elongate, syntectonic granite bodies (described below) which were intruded along the contact between these low-grade metamorphic rocks and the older gneisses that lie to the north. The terrane to the south of the B-L line is also made up of older gneisses, but those gneisses are intruded by a variety of Hercynian granites of different ages. The continuation of the B-L tectonic line to the west could lie between the migmatites of Kayserberg-Trois Épis and the Lower Carboniferous of Marckstein (north of Treh), or it could intersect the line of klippen in the southern Vosges (MAASS, 1981; FLUCK *et al.*, 1980).

The oldest sediments in the B-L zone are deep water shales, cherts, red siltstones and sporadic calcareous olistostromes (SITTIG, 1969; MAASS and STOPPEL, 1982). These must originally have been deposited over a wide area (as indicated by their much more widespread occurrence in the southern Vosges). The fact that in the entire Schwarzwald massif the only place that they are preserved (as effectively unmetamorphosed sediments) is within the B-L zone, requires that this zone was sharply downdropped with respect to the mid-crustal high-grade gneisses that comprise most of this region.

Sheared granites (dated at 360–330 Ma) in the Black Forest and the Vosges all seem to be tied to these major tectonic lines. The best example of such a sheared granite in the Schwarzwald is the Rand Granite pluton, which is only about 1–2 km wide, but which stretches almost the entire length of the B-L zone (Fig. 2). The later Hercynian magmatic activity at 330–280 Ma is obviously free of any such ties to the E–W structures that control the shapes and deformational features of these earlier Hercynian granites.

FLUCK *et al.* (1980) believe that these tectonic lines are genuine thrusts, described as follows: Immediately at the contact of the thrusts, the overridden, strongly mylonitized Paleozoic sedimentary rocks are metamorphosed, but away from the thrust the same units are essentially unmetamorphosed. The higher-grade gneisses in the opposed, overriding unit also display strong mylonitization, shearing, and drag folds. On the north boundary of the B-L zone EISBACHER *et al.* (1989) use seismic reflection profiles to trace this north-dipping structure (termed the Todtnau thrust zone) to a depth of 12 km into the continental crust. In contrast to the above interpretations, SITTIG (1981) has interpreted most of the features within the B-L zone in terms of wrench-fault tectonics.

Hercynian granitic rocks

The Hercynian granites in the Schwarzwald have been studied by a large number of workers, including EMMERMANN (1977), who argued that as they evolved these magmas had a progressively deeper crustal origin through time. In the southern Schwarzwald, all of these granites are intruded either within the B-L zone (syntectonic), south of the B-L zone (late-tectonic), or adjacent to and truncating the B-L zone (post-tectonic).

At an early stage, relatively small leucogranite stocks were emplaced, uplifted, and rapidly eroded, as they are found as pebbles in the synorogenic Lower Carboniferous conglomerates. The various deformed granites in the B-L zone (Rand, Klemmbach, etc.) also probably belong to this early phase of activity. One interesting pluton in the B-L zone that was intruded adjacent to the Rand Granite but which is much less deformed than that body, is the Münsterhalden Granite (Fig. 2). This narrow, elongate pluton is probably the youngest pluton emplaced wholly within the B-L zone, based on its relative lack of internal deformation and shearing compared to the other B-L zone granites, and also because (as we demonstrate below) it is the only granite in the B-L zone that has not been appreciably hydrothermally altered. SITTIG (1981) has proposed that this pluton was tectonically emplaced, based on fault contacts and lack of contact metamorphic effects.

A number of larger, less deformed plutons to the south of the B-L zone (*e.g.*, the Malsburg, Lenzkirch, and St. Blasien; see Fig. 2) were probably intruded next (METZ and REIN, 1958). EMMERMANN (1977) suggests that this episode of granitic magmatism commenced with melting of plagioclase- and biotite-rich paragneisses, producing large volumes of biotite granite (*e.g.*, St. Blasien). This was followed by a major change in tectonic style of magma emplacement during the period about 300–320 Ma, at which time melting at deeper crustal levels is thought to have formed K-rich, H_2O-undersaturated magmas that intruded to higher crustal levels. The large, undeformed, coarser-grained, two-mica granite plutons that truncate the east-central part of the B-L zone (Fig. 2) were emplaced at this time (*e.g.*, Bärhalde, Schluchsee, and Ursee).

Geochronology

Despite the large amount of geochronological work in the Schwarzwald, we do not yet know the exact emplacement ages of most of these plutons. However, the *relative* ages of emplacement can in many cases be constrained by the detailed geological mapping (*e.g.*, METZ and REIN, 1958).

On the basis of geological relationships, a crude subdivision of the igneous activity into four stages can be made. In decreasing order of age these are: (1) syntectonic, highly deformed granites such as the Rand and Klemmbach granites, probably emplaced roughly synchronous with low pressure-moderate temperature metamorphism of the B-L zone rocks; (2) late-tectonic, less-deformed granites (*e.g.*, St. Blasien, Malsburg, Münsterhalden); (3) post-tectonic, undeformed plutons such as the Bärhalde and Schluchsee granites; and (4) volcanic and subvolcanic igneous rocks intercalated with the Late Carboniferous and Permian clastic basin fills.

The inability to obtain accurate radiogenic ages of emplacement particularly applies to the early, highly deformed plutons in the B-L zone, as these have all undergone considerable post-emplacement deformation and recrystallization, thereby obscuring their primary magmatic ages. Perhaps the most reliable radiogenic ages are the Rb-Sr whole-rock ages of LEUTWEIN and SONET (1974), who have reported the following ages (in Ma) for some of the older granites of the study area: Rand (346 ± 15), Klemmbach (340), Münsterhalden (322 ± 15), and Malsburg (314 ± 15). The above isotope geochronology agrees quite well with the geological relationships described above.

The ages of the granitic rocks also are constrained by cooling ages on metamorphic minerals within the adjacent high-grade metamorphic rocks. Rb-Sr and K-Ar ages of hornblende, muscovite, and biotite have yielded ages of 330–325 Ma (biotite and muscovite) and 328–342 Ma (hornblende) (VENZLAFF, 1971; VON DRACH, 1978; LIPPOLT *et al.*, 1986; KROHE and EISBACHER, 1988). Granitic dikes which appear to cut the regional gneissic foliation, but themselves have a distinct schistosity, have given muscovite K-Ar ages of 341–329 Ma (LIPPOLT *et al.*, 1986). Although there is a crying need for more work (particularly U-Pb dating of zircon) the combined data are consistent with an age for the peak of low-pressure metamorphism at around 330–340 Ma, and this age range is probably contemporary with intrusion of the earliest syntectonic granites. Interestingly, this overlaps exactly with the age of the latest sedimentation documented in the B-L zone, the terrestrial, Late Visean (330–340 Ma) coarse clastic sediments. This means that metamorphism at depth was going on simultaneous with sedimentation at the surface.

This is extremely similar to the situation in the Hercynian of the Pyrenees where a similar style of low-pressure metamorphism at depth (~340–310 Ma, see summary in BICKLE *et al.*, 1988) also accompanied sedimentation at the surface (see WICKHAM and OXBURGH, 1986). The difference between the two situations is that in the Pyrenees this sedimentation was marine, whereas in the Schwarzwald it was subaerial.

There are slightly better age constraints on the late- and post-tectonic granites and high-level porphyry dikes which cut them. The best dated plutons are the post-tectonic plutons (Bärhalde and Schluchsee) and these of course, provide a minimum age boundary for emplacement of the demonstrably older, deformed plutons. MÜLLER-SOHNIUS *et al.* (1976) conclude that these two plutons were intruded virtually simultaneously at about 304 Ma, whereas WENDT *et al.* (1974) suggest that the Schluchsee was intruded first (≈315 Ma) and the Bärhalde much later (≈290 Ma). Rb-Sr, K-Ar and Ar-Ar ages on biotite and muscovite from these and other somewhat earlier-stage granites range from 327 to 320 Ma in the southern Schwarzwald (WENDT *et al.*, 1970; BREWER and LIPPOLT, 1972; LIPPOLT *et al.*, 1983; LIPPOLT and RITTMANN, 1984). The porphyry dikes have been dated at 323–317 Ma. The post-orogenic Permo-Carboniferous basin volcanics give ages ranging from 307–286 Ma (Rb-Sr on biotite and apatite). This overlaps with the older end of the range of ages for the "late granodiorites" in the Pyrenees.

The combined evidence from the sediments and the ages on the granites and metamorphic minerals implies that metamorphism accompanied sedimentation at the surface. This rules out the possibility that the metamorphism was accompanying regional uplift as in collision-type scenarios. The localized pockets of terrestrial sediments of 330–340 Ma age in the B-L zone strongly suggest that local rifting occurred within a major belt of strike slip-extensional deformation. The oxygen isotope data to be discussed below fit this picture perfectly, and the contrast in the type of water involved in hydrothermal metamorphism in the Pyrenees and the Schwarzwald is mirrored by the contrasts in syn-metamorphic sediment type.

OXYGEN ISOTOPE DATA

Our detailed study of $^{18}O/^{16}O$ ratios in more than 200 samples of igneous and metamorphic rocks and their coexisting minerals from the southern Schwarzwald (Black Forest) covers an area of more than 3000 km^2 from Basel and Freiburg eastward to Lenzkirch (Fig. 1). The $^{18}O/^{16}O$ sample localities in the vicinity of the B-L zone are shown in Fig. 3; other localities lie off this figure to the north and to the south. All of the whole-rock $\delta^{18}O$ analyses are reported graphically in Fig. 4, together with available data from MAGARITZ and TAYLOR (1981), HOEFS and EMMERMANN (1983), and SIMON and HOEFS (1987). The whole-rock $\delta^{18}O$ values were determined by conventional fluorination techniques (TAYLOR and EPSTEIN, 1962). Representative portions of hand-specimen-sized samples of the rocks were pulverized and ground to −200 mesh in a SiC mortar, and then reacted with fluorine gas. The resulting oxygen gas then was converted into CO_2 and analyzed in a mass spectrometer. The data are reported in per mil relative to SMOW (Standard Mean Ocean Water). In our laboratories, NBS-28 has a $\delta^{18}O = +9.60$ on this scale.

A condensed version of the present paper was published two years ago at the EPSTEIN 70th Birthday Symposium (TAYLOR *et al.*, 1989). Subsequently, SIMON (1990) presented new whole-rock $\delta^{18}O$ and biotite-chlorite δD values in 31 samples from four Hercynian granite plutons as follows: St. Blasien (+3.7 to +8.8, −65 to −108); Albtal (+8.9 to +10.4, −86 to −105); Bärhalde (+7.9 to +11.1, −66 to −91); and Schluchsee (+9.5 to +11.4, −60 to −90). These data provide additional evidence to that reported by SIMON and HOEFS (1987) concerning the meteoric-hydrothermal ^{18}O-depletions in these four granites, confirming that such effects are virtually non-existent in the late-stage Bärhalde and Schluchsee plutons and minor in the two earlier plutons. SIMON (1990) does not report any dramatic ^{18}O depletions similar to those in the B-L zone samples discussed below in the present paper. Three of his samples from the St. Blasien granite are slightly depleted in ^{18}O, but only one of these has $^{18}O < +4.9$. The other 28 samples studied by SIMON (1990) range from $\delta^{18}O = +6.8$ to +11.4, and would all plot as black dots on Fig. 3.

DISCUSSION

Low-^{18}O rocks in the vicinity of the B-L zone

Because of the large number of sample localities shown on Fig. 3, for clarity we do not letter in the actual whole-rock $\delta^{18}O$ values. Instead, we show three categories of data-points, and if we assume that essentially all samples started out with $\delta^{18}O > +7$ (which is justified below), then: (1) samples with $-2.3 < \delta^{18}O < +3$ must have been depleted in ^{18}O by at least 4 to 13 per mil; (2) samples with $+3 < \delta^{18}O < +6$ have been lowered by at least 1 to 8 per mil; and (3) samples with $\delta^{18}O > +6$ are either unchanged in $\delta^{18}O$ or they have been depleted in ^{18}O by only a few per mil. We cannot be more precise about these ^{18}O depletions because the original protoliths of the hydrothermally metamorphosed samples in the Schwarzwald are lithologically very diverse and undoubtedly had variable initial $\delta^{18}O$ values. However, based on a wealth of $^{18}O/^{16}O$ data from other Hercynian terranes all over Europe (*e.g.*, see review by SHEPPARD, 1986a), it is reasonably certain that all of the rocks studied in this work started out with $\delta^{18}O > +7.5$. In the entire European Hercynian $\delta^{18}O$ values lower than this are typically found only in mafic igneous rocks, and such rocks were not analyzed in the present study. In particular, most of the granitic rocks probably had initial $\delta^{18}O > +8.5$, and many of the Upper Devonian-Lower Carboniferous detrital sediments in the B-L zone very likely started out with $\delta^{18}O$ values as high as +13 to +17 or higher, because similarly high $\delta^{18}O$ values are typical of such sedimentary rocks throughout the world. Note that a number of the lowest $\delta^{18}O$ values observed in the study area are from these sediments, indicating that some of these whole-rock samples may have been depleted in ^{18}O by as much as 15 to 20 per mil (Fig. 4). A single analyzed chert sample ($\delta^{18}O = +6.9$) has apparently been depleted in ^{18}O by more than 20 per mil (because marine cherts typically are deposited with $\delta^{18}O > +30$).

In this study, we obtained 39 whole-rock analyses with $-2.3 < \delta^{18}O < +3$. Except for a single sample near the contact of a quartz porphyry that cuts the

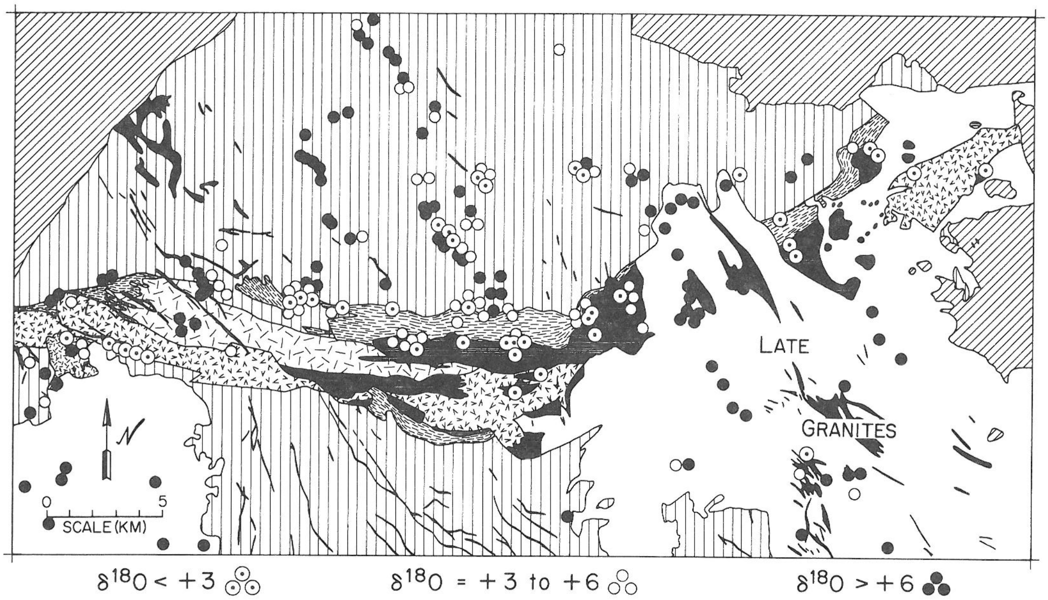

FIG. 3. Same map as in Fig. 2, showing the oxygen isotope sample localities studied in this work, but with the lithologic symbols and the generalized NW-trending fracture set both deleted for clarity. The samples are divided into three groups: (1) Whole-rock $\delta^{18}O < +3$ is indicated by large white dots with black centers; (2) $+3 < \delta^{18}O < +6$ is shown by small white dots; and (3) whole-rock $\delta^{18}O > +6$ is indicated by small black dots. Note the concentration of low-^{18}O rocks in the vicinity of the B-L zone and along the zone of northwest-trending fractures in the gneiss complex just north of the B-L zone (the major fractures are schematically shown in Fig. 2). Note also the concentration of high-^{18}O values throughout the Late Hercynian granite plutons that truncate the B-L zone (28 additional black dots could have been added to that part of the map if we had utilized the new data of SIMON, 1990).

St. Blasien granite, every one of the other 38 samples is from a locality less than about 5 km from the contact of the Rand Granite of the B-L zone (Figs. 3 and 4). No other samples with $\delta^{18}O < +3$ have been found outside this narrow zone anywhere in the Schwarzwald, either by us or by HOEFS and EMMERMANN (1983) or SIMON (1990). We also obtained 59 whole-rock analyses with $+3 < \delta^{18}O < +6$ within the outcrop area delineated in Figs. 2 and 3. Of these 59 moderately ^{18}O-depleted samples, only 9 (*i.e.* 15%) are from localities farther than 5 km from the contact of the Rand Granite. The geographic correlation with proximity to the Badenweiler-Lenzkirch tectonic line could not be more clear.

Even more compelling than the above correlations, however, is the fact that (if we exclude the less deformed, younger Münsterhalden Granite) of the 60 samples that were collected well within the boundaries of the B-L zone, only one has a $\delta^{18}O > +6$. Of the other 59 samples, 30 have $\delta^{18}O < +3$, and 29 have $\delta^{18}O$ between +3 and +6. In otherwords, from the entire set of Schwarzwald samples, 77% (30/39) of the sub-set of extremely ^{18}O-depleted samples were collected from within the confines of the narrow B-L zone, and 97% of these very low-^{18}O samples (38/39) lie within about 5 km of this zone.

The geographic distribution of ^{18}O-depleted whole-rock samples shown in Figs. 3 and 4 implies intense focusing of meteoric-hydrothermal metamorphism along the B-L zone. Based on many earlier studies (*e.g.*, as reviewed by TAYLOR, 1988, 1990; CRISS and TAYLOR, 1986), it is clear that low-^{18}O meteoric-hydrothermal fluids are the only materials on Earth that could have produced such dramatic oxygen isotope effects. The geological features and age-dating described above require this meteoric-hydrothermal activity to have taken place in the Lower Carboniferous at sometime within the interval 320–360 Ma, probably starting at the time of intrusion of the elongate Rand Granite pluton. This is proved by the striking ^{18}O depletions (whole-rock $\delta^{18}O = -2$ to $+4$) that exist all along the B-L zone (Fig. 3) and which are also observed *throughout* the highly deformed, syntectonic Rand Granite, together with the fact that such ^{18}O depletions are *not* observed in the post-tectonic granites. The Rand Granite and its associated migmatites are confined to the B-L zone, and although this elongate pluton

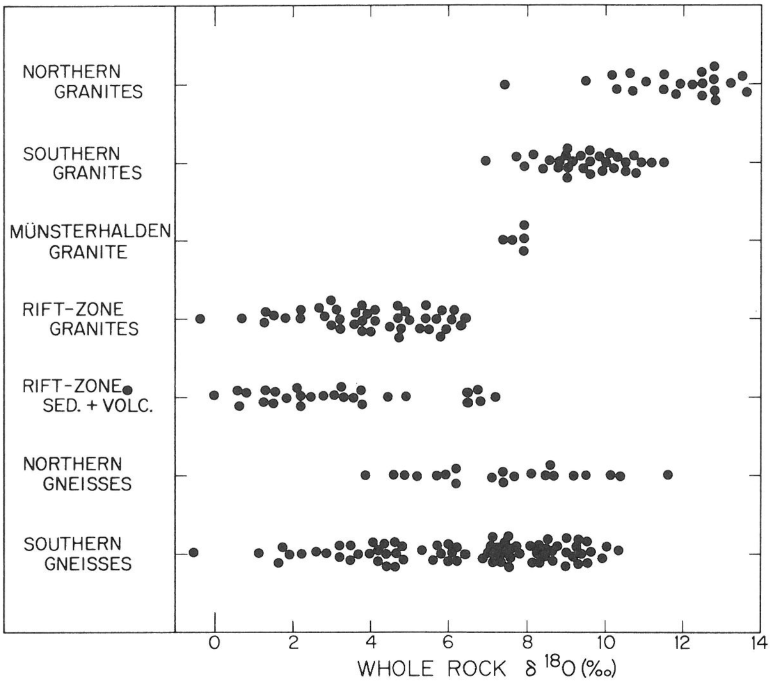

FIG. 4. Whole-rock $^{18}O/^{16}O$ ratios of various samples from the Schwarzwald, Germany, from this work, from MAGARITZ and TAYLOR (1981) and from HOEFS and EMMERMANN (1983). The samples labeled as Northern Gneisses and Northern Granites are from the northern half of the Schwarzwald massif, mostly well off the top of the map shown in Fig. 1. The lowest-^{18}O samples of the Southern Gneisses all lie within a few km of the B-L rift zone, either in close proximity to the Rand Granite or in the vicinity of a major northwest-trending fracture system that locally offsets the Rand Granite. The rift-zone (= B-L zone) granite data-points in the figure are mainly from the Rand Granite, but they also include the Klemmbach Granite and a couple of other (sheared and foliated) granites analyzed from the B-L zone. The only granitic samples from the B-L zone that are plotted separately are those from the Münsterhalden Granite. The rift-zone sedimentary and volcanic data-points represent analyses of sedimentary and volcanic rocks from the DS and LCVS units of the B-L zone shown on Fig. 2. Note that one of these samples has an extremely low $\delta^{18}O$ (−2.3) and plots off the diagram to the left.

is split apart and truncated by the later-stage, undeformed, high-^{18}O Hercynian granites (Bärhalde, Schluchsee), the Rand Granite *and* its associated low-^{18}O signature extend through virtually the entire length of the B-L zone from Lenzkirch almost all the way to Badenweiler (Figs. 1 and 2). Strong ^{18}O depletions are also very pronounced in the "classic" migmatites (MEHNERT, 1968) found along the contacts of the Rand Granite, both against the anatectic gneisses on the north and against the metasediments and metavolcanics to the south (Fig. 3).

Low-^{18}O values in gneisses cut by the NW-trending fracture systems

Although the effects are much weaker than those observed in the B-L zone, measurable ^{18}O depletions also occur locally up to 10–15 km north and south from the B-L zone, associated either with the earliest Late Hercynian granites (*e.g.*, St. Blasien) or with northwest-trending fractures in the basement gneisses. The general patterns of these NW-trending fractures are shown in Fig. 2.

These fractures were clearly conduits for the meteoric-hydrothermal fluids, because: (1) in the field there is a clear-cut geographic association between areas of intense fracturing and the occurrence of low-^{18}O rocks, both on a regional scale (Fig. 2) as well as on an outcrop scale (readily observed in road cuts); (2) the fractures that permeate the low-^{18}O outcrops of gneiss are typically "healed" by metamorphic-hydrothermal recrystallization; and (3) there is extensive replacement of the original gneiss mineralogy by new hydrothermal minerals such as epidote and chlorite.

These fracture systems clearly pre-date the Late Carboniferous to Permian quartz porphyries and granite porphyries shown in black on Fig. 2, because the fractures acted as conduits for these late Hercynian magmas. The orientation and age of formation of this fracture system are both compatible with our model for the origin of the B-L zone as a pull-apart associated with a major strike-slip fault (see below), because such *en echelon* fractures commonly are oriented about 45° to the trend of the wrench fault which produced them.

$^{18}O/^{16}O$ ratios of coexisting minerals and juxtaposed rocks

In the course of our studies on the Schwarzwald we obtained a large number of $^{18}O/^{16}O$ analyses of coexisting minerals (mainly quartz and feldspar), as well as considerable data on directly adjacent whole-rock samples or samples from different lithologies in the same outcrop. These data will be presented in future publications by us, so in this brief summary we only mention the features of this data set that are pertinent to our interpretations of the geological history of the B-L zone.

A remarkable aspect of the oxygen isotope data on coexisting quartz-feldspar pairs from the gneisses, schists, migmatites, and granites in the B-L zone is its heterogeneity. The isotopic fractionations (reported as Δqtz-feld = δqtz − δfeld) range widely, from near-equilibrium Δ-values of one to two per mil to strikingly large Δ-values of five to eight per mil, values which are typical of the (subsolidus) meteoric-hydrothermal alteration of most epizonal plutons on Earth. In several samples δ^{18}Oqtz is very low (+3 to +6) and Δqtz-feld less than three per mil, indicative of either (1) crystallization from pockets of low-^{18}O magma (probably formed by partial melting of rocks previously hydrothermally altered); or (2) much higher-temperature and/or longer-lived hydrothermal exchange with low-^{18}O fluids, based on the fact that quartz is so much more resistant to $^{18}O/^{16}O$ exchange than is feldspar (*e.g.*, see TAYLOR, 1988; GREGORY *et al.*, 1989).

The same level of heterogeneity is observed in whole-rock $\delta^{18}O$ values from the juxtaposed melanosome-leucosome pairs of B-L zone migmatites (MAGARITZ and TAYLOR, 1981). A few of these pairs tend to have similar $\delta^{18}O$ values, with the granitic part being less than one per mil higher than the more mafic part, typical of most other migmatites that have been studied isotopically, and which is to be expected if the mineral assemblages closely equilibrated at high temperatures. However, in several of the B-L zone samples the granitic portion of the migmatite is either two to five per mil higher in $\delta^{18}O$ than the coexisting more mafic portion or in an equal number of other cases the rock pairs display reversed fractionations of one to three per mil; both situations are incompatible with isotopic equilibrium among the assemblages.

What are we to make of the above-described isotopic heterogeneities among such closely coexisting or adjacent materials? First, we must conclude that the metamorphic-hydrothermal-temperature history of the area either has been (1) very complex, or (2) rocks and granitic melts with widely divergent hydrothermal or temperature histories have somehow been assembled together and tectonically juxtaposed within the B-L zone. The actual situation probably involves a combination of these phenomena. In particular, we believe that these isotopic data are telling us that this rift zone had a complex origin and evolution, and that there probably have been major geologic modifications of the B-L zone that post-date the early stages of meteoric-hydrothermal activity (*e.g.*, post-rift deformation and continued water/rock interactions along strike-slip faults or thrust faults, or overlapping hydrothermal systems at different temperatures as a result of emplacement of new igneous bodies). This interpretation of these heterogeneous oxygen isotope fractionations coincides nicely with our preferred model for the B-L zone, described below.

Münsterhalden Granite and westernmost outcrops of Rand Granite

The only part of the B-L zone where the kinds of ^{18}O depletions described above are not present is: (1) within the relatively undeformed Münsterhalden Granite body (Figs. 2 and 3); and (2) in the northern part of the extreme western extension of this tectonic line, where five samples have $\delta^{18}O$ = +6.2 to +8.9 and the other three have $\delta^{18}O$ = +5.4 to +5.8; in this area the outcrop width of Rand Granite narrows to less than a few hundred meters and then virtually vanishes.

The elongate Münsterhalden Granite body was apparently emplaced within the B-L zone after the main stage of hydrothermal activity ceased, because like the post-tectonic plutons it has undergone little or no ^{18}O-depletion (*e.g.*, compare Figs. 2, 3, and 4). It is, however, *slightly* more ^{18}O depleted than these latest-stage Hercynian plutons (Fig. 4), and it may have been incipiently affected by the hydrothermal fluids. There is also the possibility that its relatively low $\delta^{18}O$ values of +7.3 to +7.9 are primary magmatic values (Could its protolith at depth have undergone a small amount of hydrothermal ^{18}O depletion prior to being partially melted?).

It thus appears that the strength of the meteoric-hydrothermal system was decreasing to the west as the volume of immediately adjacent Rand Granite became smaller and smaller. This is compatible with the geological relationships (Fig. 2) that indicate that the Rand Granite was the principal "heat engine" driving the B-L meteoric-hydrothermal circulation system. It is logical to assume that the strength of the hydrothermal system was also decreasing with time, perhaps coming to a halt as the Rand Granite underwent final crystallization and cooling. Both the geographical effect and the temporal effect probably worked together to diminish the intensity of the hydrothermal system in the westernmost B-L zone at the time of emplacement of the Münsterhalden Granite.

The $^{18}O/^{16}O$ data, taken together with the narrow, elongate aspect ratio of the outcrops of Münsterhalden Granite strongly suggest that E-W structural features in the B-L zone were still active in guiding granitic pluton emplacement in the upper crust, even though the episode of faulting was coming to a close. Certainly, soon after this the geologic situation changed dramatically as the large latest-stage Hercynian granitic bodies like the Bärhalde and Schluchsee were emplaced. These large masses of granite sharply truncate the east-trending faults that lie within and define the B-L zone, and there is no evidence whatsoever that any of these latest-stage Hercynian magmas infiltrated the B-L zone in the way that the Rand or Münsterhalden Granites did. Perhaps by Bärhalde-Schluchsee time the entire B-L zone at its present level of exposure either had evolved into a new stress regime less favorable for open fractures, or perhaps had subsided to greater depths, or both (in order to avoid the inevitable low-^{18}O meteoric-hydrothermal interactions).

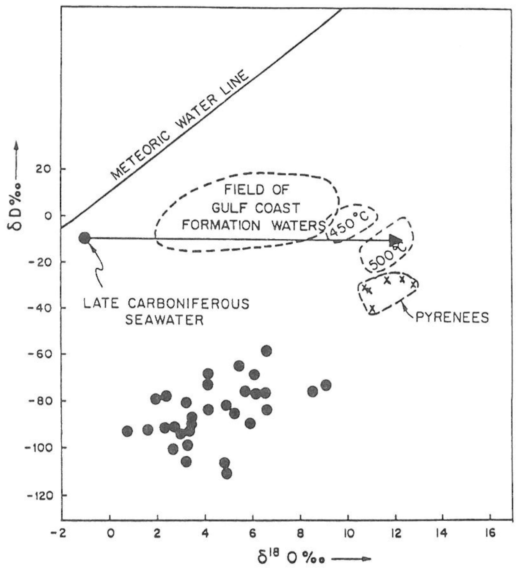

FIG. 5. The black dots represent analyses of whole-rock $\delta^{18}O$ and δD of biotite, hornblende, or chlorite (rare) for samples of the older gneisses, migmatites, schists, and sheared granites within the Badenweiler-Lenzkirch zone in the southern Schwarzwald. The δD values are from MAGARITZ and TAYLOR (1981). The uppermost four samples with highest δD and highest $\delta^{18}O$ are from the extreme western end of the B-L zone (see text). Note that these B-L zone Schwarzwald samples are all much lower in $\delta^{18}O$ and δD than the Hercynian igneous and metamorphic rocks from the Pyrenees (crosses) analyzed by WICKHAM and TAYLOR (1985); the Pyrenees samples appear to have formed from high-temperature marine waters (the calculated equilibrium fields are shown at 450° and 500°C), whereas the Schwarzwald samples clearly formed from exchanged meteoric-hydrothermal fluids that would have had $\delta D \approx -40$ to -65 and $\delta^{18}O \approx -2$ to $+6$, all derived from original ground waters that had $\delta^{18}O \approx -6$ to -9 (see text).

Later Hercynian granites

Meteoric-hydrothermal activity clearly must have largely terminated prior to truncation of the B-L rift zone by the latest-stage (*ca.* 290–315 Ma) Hercynian granites just southwest of Lenzkirch (Bärhalde, Ursee, Schluchsee), because these granites in general show only minor meteoric-hydrothermal effects and little or no subsolidus ^{18}O depletions. We analyzed 16 whole-rock samples from these plutons and SIMON (1990) reports another 17 analyses. This entire combined data set exhibits a $\delta^{18}O$ range only from +8 to +11.

D/H ratios

MAGARITZ and TAYLOR (1981) determined the δD values of 31 samples collected all along the B-L zone; these range from −60 to −111 (Fig. 5), and are mainly biotite, but include some hornblende and rare chlorite (as well as some impure biotite and hornblende mineral separates that contain minor chlorite). Most of the analyzed rocks are only incipiently chloritized, so it is clear that much of the hydrothermal metamorphism occurred at moderately high temperatures, in the stability field of biotite. Many of these samples were collected either along the contacts of the Rand Granite or within 100 meters of its contact, both on the north against the gneiss complex, or along its contact against Upper Paleozoic metasediments on the south.

The Schwarzwald data-points on Fig. 5 display a crude trend subparallel to the Meteoric Water Line (extending toward the analogous data-points from the Pyrenees). The most logical interpretation of this trend is that it represents an isotopic shift in the OH-bearing minerals from their original igneous and/or metamorphic values downward and to the left toward values that indicate thorough exchange with large volumes of the aqueous fluids. The four samples that are highest in δD and $\delta^{18}O$ on this diagram are in fact from the extreme western end of the B-L zone, where the hydrothermal metamorphism was apparently very weak (see above).

The pattern of data points shown on Fig. 5 is not typical of the simpler geological situations encountered in most meteoric-hydrothermal systems studied to date, for example where a single, undeformed epizonal pluton is emplaced into permeable country rocks. Ordinarily that kind of situation produces a characteristic "inverted-L" shaped trajectory, *i.e.*, first a δD shift directly downward and then a $\delta^{18}O$ shift horizontally to the left as the water/rock ratio increases (*e.g.*, see TAYLOR, 1977). Thus the results on Fig. 5 seem to *demand* a much more complex geologic or hydrothermal history for the B-L zone.

One possible interpretation of the data on Fig. 5 is that the early stages of water/rock interaction in the B-L zone did indeed produce a simple "inverted-L" shaped pattern in the rocks, but that subsequently the area underwent other metamorphic events that evolved a series of "mixing lines" between high-δD, high-$\delta^{18}O$ samples and nearby low-$\delta^{18}O$, low-δD samples, thereby smearing out the isotope pattern. Another interpretation is that the samples shown on Fig. 5 represent structural juxtaposition of rocks with widely different hydrothermal histories. Still another interpretation is that two or more water sources, with different isotopic compositions, were involved (*e.g.*, sea water *and* meteoric water). Finally, it is possible that the hydrothermal activity occurred in multiple episodes over a long period of time, long enough for the climate to change and the δD of the local meteoric ground water to shift by more than 20 per mil. The latter is probably the least likely explanation, based on what we know about the paleolatitude of this area in the Late Paleozoic (see below), and also because nearby granites intruded well after the Rand Granite show a range of δD values practically identical to those of the B-L zone (MAGARITZ and TAYLOR, 1981; SIMON, 1990).

Any or all of the above explanations may apply to the B-L zone samples represented by the data points in Fig. 5. Inasmuch as we know from the paleontological evidence that the marine-to-freshwater transition in the sediments of the B-L zone did occur fairly close in time to the age of emplacement of the Rand Granite, the explanation involving two isotopically distinct kinds of water has a good deal of attraction (and it might also explain the crude trend on Fig. 5 toward the Pyrenees data points!). This concept is developed more fully below in a later section.

In spite of the above complications, and also in spite of some inherent problems of retrograde D/H exchange and of applying the D/H fractionations between OH-bearing minerals and H_2O (because of differences in Fe/Mg and Fe/Al chemical compositions of the various OH-bearing minerals, *e.g.*, see SUZUOKI and EPSTEIN, 1976), it is instructive to examine the δD values of the most ^{18}O-depleted group of samples in Fig. 5. This is the group that is probably most representative of exchange with the end-member meteoric waters of the B-L zone, regardless of which of the interpretations in the above list one favors (*e.g.*, see TAYLOR, 1977). The 14 samples with whole-rock $\delta^{18}O < +4$ have δD values of ranging from -79 to -106. However, most of these samples show a δD variation only from -90 to -100. Applying a plausible range of hydrothermal temperatures (350–500°C) and using the calibration curves of SUZUOKI and EPSTEIN (1976), one obtains a range of δD values of about -40 to -65 for the original meteoric ground waters of the region. Such values are typical of sub-tropical regions of the Earth today (*i.e.*, southeastern U.S.A., Mediterranean Sea, Southeast Asia; see SHEPPARD, 1986b). If we use these values and then go horizontally over to the Meteoric Water Line, the initial $\delta^{18}O$ values of the groundwaters can be calculated to have been about -6 to -9.

There is little doubt that the paleolatitude of the Schwarzwald was close to or within the tropics during the Visean and most of the Carboniferous (SCOTESE and MCKERROW, 1990). The climate at the time was certainly hot, because evaporites and carbonate platform sediments were being deposited immediately to the north (ZIEGLER, 1982). The preservation of terrestrial plant fossils in the Visean of the B-L zone also provides evidence that the climate was wet, because it is only in humid climates that such fossils are commonly preserved (A. M. ZIEGLER, pers. comm., 1991). The combined evidence suggests that at the time that the B-L hydrothermal system developed, a humid sub-tropical climate prevailed, and in view of the low paleolatitudes, it is unlikely that local meteoric waters were ever extremely low (*e.g.*, $\delta^{18}O$ of the local fresh waters could not possibly have been lower than -10, a conclusion in good agreement with our calculations using the data in Fig. 5).

Note that the δD values of most of the B-L zone samples are not much different from the typical values of -50 to -85 observed in most igneous and metamorphic rocks on Earth (*e.g.*, see TAYLOR and SHEPPARD, 1986). However, the *combination* of extremely ^{18}O-depleted and moderately D-depleted rocks is nevertheless conclusive evidence for the strong involvement of meteoric-hydrothermal fluids in the metamorphism of the B-L zone.

Northern Schwarzwald

Such ^{18}O-depleted rocks as described above from the B-L zone have *not* been found anywhere in the northern Schwarzwald, either by us or by HOEFS and EMMERMANN (1983). Across the entire Schwarzwald massif, such extreme ^{18}O depletions are confined to the vicinity of this narrow tectonic line. Although weaker ^{18}O depletions are found locally over a much broader area, they also are basically confined to the southern Schwarzwald, either to the B-L zone or to the set of NW-trending fractures, although a few examples also are associated with certain early-stage Hercynian granites (*e.g.*, St. Blasien).

Note also that the primary magmatic $\delta^{18}O$ values of late-stage Hercynian granites from the northern Schwarzwald are higher than those of their post-rift equivalents in the south (Fig. 4). The sequence of increasing ^{18}O in these later granites thus correlates with their geographic proximity to the Badenweiler-Lenzkirch tectonic line. Some of these geographic effects are undoubtedly attributable to subsolidus hydrothermal alteration, but most of them seem to be primary magmatic effects. It is thus tempting to speculate that the reason why the younger Hercynian granites in the southern Black Forest tend to be lower in ^{18}O then those farther north is because they may have formed by melting of gneisses that had earlier become somewhat depleted in ^{18}O by the major meteoric-hydrothermal-metamorphic event that was confined to the south, and that increased in intensity toward the B-L tectonic line. This correlation becomes even more compelling if the Münsterhalden Granite is added to the picture (Fig. 4), because this pluton is even lower in ^{18}O than the other southern granites and it was emplaced totally within the B-L zone.

A RIFT-ZONE MODEL FOR THE B-L ZONE

Extensional tectonics in the Hercynian of Europe

Although traditional interpretations of late Hercynian (Variscan) orogenesis in Western Europe have invoked collisonal tectonic settings (*e.g.*, see MATTE and ZWART, 1989), recently several workers have suggested that instead, the characteristic low-pressure metamorphic sequences were generated within, or were associated with, zones of crustal extension (*e.g.*, WICKHAM and OXBURGH, 1985, 1987; WICKHAM and TAYLOR, 1990, 1985, 1987; BICKLE *et al.*, 1988; DESAINT BLANQUAT *et al.*, 1990; ECHTLER and MALAVIELLE, 1990). In the Pyrenees the evidence for deep circulation of marine waters, together with the evidence for contemporeneity of metamorphism at depth and marine sedimentation at the surface, are both incompatible with a model of regional uplift associated with continent-continent collision, as is the complete absence those rock types commonly found within collision zones, such as high-pressure metamorphic assemblages or ophiolite complexes.

Clearly, major regional crustal extension was occurring throughout Western Europe from latest Carboniferous time onward (MÉNARD and MOLNAR, 1988). These authors present an interesting map comparing the Permo-Carboniferous basins in central Europe with the sub-parallel grabens and half-grabens linked by normal and strike-slip faults in the Basin and Range Province of western North America. The outcrops and subcrops of these Permo-Carboniferous basins define linear belts that trend roughly E–W right across the Vosges and Schwarzwald massifs, before bending SW toward the Massif Central. The basins are hundreds of km in length and typically 5 to 25 km in width. Although they are clearly younger, there might be an evolutionary connection between these regional structural features and the down-dropped block of Lower Carboniferous sediments and volcanics in the B-L zone. MÉNARD and MOLNAR (1988) also point out that the normal faults that are found in some of the Hercynian basins have been re-activated as reverse faults; thus, even though the B-L zone exhibits some features attributable to thrusting (FLUCK *et al.*, 1980), compressional deformation need not have been dominant during the entire evolution of the B-L zone.

Comparison with the Hercynian of the Pyrenees

Except for involvement of low-D, low-^{18}O meteoric waters instead of high-D marine formation waters (Fig. 5), the Schwarzwald results are comparable with data from the Trois Seigneurs Massif, Pyrenees, where a rift-zone setting is also hypothesized and where analogous prograde hydrothermal metamorphism and somewhat analogous syn- and post-metamorphic granites are documented (WICKHAM and TAYLOR, 1985). The contemporeneity of metamorphism, anatexis, and granite emplacement with marine sedimentation at the surface (in the Pyrenees) and with terrestrial sedimentation at the surface (in the Schwarzwald) is a particularly striking parallel. Thus, rift-related, high thermal-gradient hydrothermal metamorphism involving marine or meteoric waters may be a common feature of Hercynian orogenic activity in Europe; in the southern Black Forest, the most likely tectonic setting for these effects would appear to be a narrow pull-apart associated with a major transform or strike-slip fault, perhaps analogous to what is going on at present along the Dead Sea rift zone in Israel or the Salton Sea trough in southern California. The enhanced fracture permeability, intrusive magmatic activity, and high heat flow associated with such pull-apart zones promotes hydrothermal metamorphism and deep convective circulation of surface-derived waters.

Emplacement of granites in dilatant zones associated with faulting

Numerous cases have been described in the literature of granites emplaced into dilatant zones of extension during regional deformation of their country rocks, either by transcurrent shear or by thrust shear. The syntectonic character of these bodies is evidenced by the concordance of the contours of petrographic, metamorphic, and structural features, and by internal rock structures that are similar in both the granite and in the country rocks (GUINEBERTEAU *et al.*, 1987; CASTRO, 1985; DAVIES, 1982; HUTTON, 1982). Typically such plutons are elongate in shape parallel to the regional vertical foliation.

Evidence for a rift origin for the B-L zone

It is the premise of this paper that the B-L tectonic line was an early Hercynian rift-zone of some type, and that the combination of (1) emplacement of a "heat engine" (*i.e.*, the Rand Granite) simultaneously with (2) the enhanced hydrologic fracture permeability attributable to the extensional tectonics, together produced a very large-sized (and long-lived?) meteoric-hydrothermal system somewhere in the time interval 320–360 Ma, based on radiogenic isotope geochronology. However, by combining the paleontological evidence for a Late Visean ($\approx$340 Ma) change from marine to fresh-water sedimentation in the B-L zone, we believe we can restrict this time interval even more tightly. The meteoric-hydrothermal event documented by the $^{18}O/^{16}O$ data could not have begun before the Late Visean, because it certainly involved meteoric waters, not seawaters. This hydrothermal system was most intense within the Rand Granite pluton and within the adjacent down-dropped block of Devonian and Carboniferous sediments and volcanics, but its effects also spread out for a distance of at least 5-10 km away from the B-L zone. Thus, an area of about 1000 km^2, centered on the B-L zone, was affected by this giant Carboniferous-age ($\approx$330–340 Ma) hydrothermal system.

Meteoric-hydrothermal effects on a small scale can be observed in a variety of tectonic environments where there has been intense deformation, for example in the mylonite zones associated with detachment faults in the metamorphic core complexes of western North America (*e.g.*, FRICKE *et al.*, 1991; LEE *et al.*, 1984) or associated with mylonites of major shear zones (*e.g.*, MCCAIG *et al.*, 1990). However, the meteoric-hydrothermal $^{18}O/^{16}O$ effects in these kinds of systems are even more tightly focused than they are in the B-L zone, occurring over distances of just a few tens of meters in the immediate vicinity of the shear zone (probably because most of them lack any good-sized magma body nearby, and thus have only limited thermal energy to drive the aqueous fluids through the rocks). These kinds of tectonic environments obviously cannot explain the data set from the B-L zone.

Our premise that the B-L zone was some type of rift is based mainly on the fact that all of the giant hydrothermal systems on Earth (both fossil and present-day) are known to be rift-related (*e.g.*, mid-ocean ridges, Iceland, Salton Sea, etc.; see CRISS and TAYLOR, 1986). For example, in this volume SOLOMON and TAYLOR (1991) discuss somewhat analogous rift-related ^{18}O-depletions associated with Jurassic igneous activity in California. Even where the individual intrusions or "heat engines" are cylindrical in shape rather than elongate, if they produced large-sized hydrothermal systems they are invariably associated with extensional tectonics (*e.g.*, the Tertiary ring dikes of the Scottish Hebrides, the Skaergaard intrusion associated with the East Greenland dike swarm, the Yellowstone Park calderas that lie on the eastward extension of the Snake River rift zone, etc.). Thus we are virtually compelled by the $^{18}O/^{16}O$ evidence to conclude that the B-L zone also must have been an extensional environment at the time of the hydrothermal activity.

To the best of our knowledge, no one in the literature has proposed a rift-zone origin for the Badenweiler-Lenzkirch tectonic line. However, although we were driven to the rift-zone hypothesis by the $^{18}O/^{16}O$ evidence, we also believe that the structural and lithological features of the B-L zone are totally compatible with such an origin, particularly its shape and the fact that the sediments are typical rift-zone lithologies made up dominantly of greywackes, arkoses, siltstones, and conglomerates intercalated with silicic and intermediate volcanic rocks.

Other than the $^{18}O/^{16}O$ evidence, probably the best indication that the B-L zone is a rift is its geometry. It is clearly a down-dropped block bounded by faults of considerable displacement, because the fine-grained sediments of Upper Devonian and Lower Carboniferous age that are the basal Paleozoic sedimentary units in this area certainly must have originally been deposited over a much larger area. However, except for their occurrence in the very narrow B-L zone they are now completely absent from the rest of the Schwarzwald massif. Clearly the B-L crustal block went down relative to the older gneisses that bound it on the north and south. However, are these boundary faults normal faults or thrust faults? The present-day geometry of the north contact between the Rand Granite and the anatectic gneiss complex certainly appears to be that of a thrust (the north-dipping Todtnau thrust zone; *e.g.,* EISBACHER *et al.,* 1989). However, we believe that this geologic boundary perhaps could have started out as a normal fault, and only later was it perhaps tilted and deformed into a thrust-fault geometry. In point of fact, EISBACHER *et al.* (1990) themselves describe the south edge of the B-L zone as a normal fault.

Because the gneisses to the north appear to have been thrust over the Badenweiler-Lenzkirch sediments, the entire zone has commonly been interpreted as a compressional (subduction-related?) feature, as for example by FLUCK *et al.* (1980) and EISBACHER *et al.* (1989). In fact, EISBACHER *et al.* (1989) in the Schwarzwald and WICKERT and EISBACHER (1988) in the Vosges, have had to develop a rather unusual model of two-sided (bivergent) crustal-scale thrusting to explain the same kinds of features that we are explaining either as a rift-zone or as a pull-apart along a strike-slip fault. A compressional setting is, however, incompatible with the observed stable isotope signatures; of course, none of this stable isotope information was available to these earlier workers, as we only formulated this concept very recently (TAYLOR *et al.,* 1989). Also, we do not deny that some of the observed structures along the B-L zone are thrust-related. It is virtually certain that this zone was at some stage the focus for such compressional deformation, but we believe that these structures have been superimposed upon earlier extensional events. However, much of the intense shearing and mylonitization observed along the B-L line may not even be thrust related; it could equally well be mainly attributable to strike-slip deformation along the B-L zone, as the "pull-aparts" that are common features of major strike-slip fault zones are themselves later closed up and sheared. SITTIG (1981) has in fact presented evidence for several kilometers of right-lateral displacement along the B-L zone, with a significant amount of slip occurring during the critical Visean time period.

We suggest that one of the reasons why a rift-zone origin for the B-L line has been overlooked is that it is extremely difficult to "look back" through all of the complex series of events (strike-slip, transpressional, transtensional, etc.) that probably have affected the B-L zone. The earliest geologic events that are clearly associated with the genesis of the B-L zone and are also the least likely to be destroyed by subsequent geologic events, are the formation of an elongate, narrow, sedimentary-volcanic trough in the Lower Carboniferous, and the intrusion of the Rand Granite along the contact between these Upper Paleozoic rocks and the basement gneisses. Based on the geological evidence cited above, in combination with the low $\delta^{18}O$ values that provide such compelling evidence for rift-zone hydrothermal activity, we believe that our extensional model for the B-L zone (closely followed or accompanied by strike-slip deformation), is much more likely than the thrust zone models favored by FLUCK *et al.* (1980) or EISBACHER *et al.* (1989).

SUMMARY AND CONCLUSIONS

Virtually all of the known areas on Earth where deep convective circulation of surface waters has produced giant hydrothermal systems and striking ^{18}O depletions on a regional scale can be shown to be associated with rift-zone magmatism and extensional tectonics (*e.g.,* the mid-ocean ridges, the sheeted dikes and gabbros of ophiolite complexes such as Oman and Cyprus, Iceland, Yellowstone Park calderas, the Salton Sea rift, the Red Sea rift, the East Greenland dike swarm, the Jurassic rift of the Mojave Desert in California, the early Tertiary volcanic centers of the Hebrides in Scotland, etc. (*e.g.,* see CRISS and TAYLOR, 1986; SOLOMON and TAYLOR, 1991). Therefore, based on our success in demonstrating that similar phenomena took place during Carboniferous time along the Badenweiler-Lenzkirch (B-L) tectonic line in the southern Schwarzwald, we suggest that in the future it may be possible to utilize $^{18}O/^{16}O$ and D/H systematics as a tool to "prospect" for rift-zones and pull-aparts, and thereby help to unravel the structure and stratigraphy of other geologically complex regions of the Earth's crust.

We believe that such an approach could turn out to be a very useful application of stable isotope geochemistry studies, because evidence of an early stage of extension can often be obscured as the stress regime changes. For example, terrane boundaries that began as a normal-fault-bounded rift-zone can evolve into a strike-slip regime, or the original faults can be re-activated as thrust faults. Plutons originally emplaced into pull-aparts along a transcurrent fault can later be sheared, stretched out, and attenuated as the local stress pattern evolves from extension to shear or transpression, etc. Therefore we can be very solicitous of the poor geologist who has the difficult task of looking back through a complex zone of deformation associated with a major, long-lived strike-slip fault zone or thrust zone, to try to identify an earlier episode of rifting and extension. Perhaps stable isotope geochemistry can help!

In spite of these complexities, if a major meteoric-hydrothermal system was established during an early period of rift-zone magmatism it will invariably produce widespread ^{18}O depletion in the rocks, and the pattern of ^{18}O depletion will reflect the location and intensity of the hydrothermal activity. More important, once large-scale $^{18}O/^{16}O$ changes have taken place in such large volumes of rocks, these $\delta^{18}O$ signatures can survive a long series of metamorphic and deformational events; the only way that such patterns can be destroyed or severely modified is for large amounts of some oxygen-bearing fluid to again move through the rocks and for them to again undergo massive and widespread $^{18}O/^{16}O$ exchange.

We believe that something like the above scenario is what happened along the Badenweiler-Lenzkirch line at about 330–340 Ma. In our view the $^{18}O/^{16}O$ systematics can only be explained by invoking some type of rift-zone magmatism, even though the geological and structural evidence for such an extensional event has escaped notice in earlier geological studies of the Schwarzwald. However, once we were driven to this particular conclusion by the $\delta^{18}O$ signatures in the rocks, we were then fortunate to find a number of pieces of evidence for this extensional event that support our hypothesis, based on the wealth of detailed studies carried out in this area by a large number of geologists over the past 100 years, many of which are put together in the magnificent geologic map compiled by METZ and REIN (1958) that we used as a base for our studies.

Using the paleontological evidence that the transition from marine to terrestrial conditions in the B-L zone occurred in the Late Visean, we also believe we can use our model to help unravel the complex and difficult geochronological relationships in this region. We can be absolutely certain from the stable isotope evidence that the B-L zone hydrothermal fluids (as well as all later-stage hydrothermal fluids that incipiently affected other Late Hercynian granites; *e.g.*, SIMON, 1990) were derived from meteoric ground waters, not seawater. Although the B-L rift must have formed prior to the marine-freshwater transition, and thus could have been the site of some early marine-hydrothermal activity (for which the evidence has since been erased), it is very clear that the major hydrothermal episode associated with intrusion of the Rand Granite "heat engine" could not have begun until after this Late Visean transition (about 340 Ma). This is because the pore spaces and fractures within the sediments and volcanics obviously could not have been permeated by the required meteoric ground waters while marine sedimentation was taking place at the surface.

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