EVIDENCE FOR ACCRETED TERRANES AND THE EFFECT OF METAMORPHISM

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ABSTRACT. Among the kinds of evidence used to demonstrate accreted terranes, four are potentially definitive: contrasting paleogeographic affinities of faunal assemblages, contrasting paleomagnetic latitudes, contrasting sedimentary facies and assemblages, and presence of oceanic ophiolite separating suspect terranes. Metamorphism tends to degrade or obliterate these kinds of evidence.

Examples of thermal modelling show that different parts of a single burial and uplift system can produce metamorphic rocks that range from blueschist facies to amphibolite facies, from being pluton-free to containing copious anatetic plutons, and from recording mineral-growth ages to recording cooling ages several tens of million years younger. Different kinds of pressure–temperature–time paths can result from a single plutonic emplacement. Thus, apparently different metamorphic and tectonic styles and the diachroneity of events in two side-by-side rock suites do not necessarily indicate their independent geologic history.

Study of metamorphic petrology and geochemistry can contribute to terrane analysis by: providing better constraints on the possible ranges of metamorphic style and history within a single terrane; establishing better controls on pressure–temperature–time paths based on mineral assemblages; improving our ability to interpret the time sequence of mineral textures, including retrograde textures or their absence; improving means to ascertain an ophiolitic origin for enigmatic ultramafic bodies found in many ancient orogens; and discovering novel ways to detect major differences in the source terranes for metasedimentary sequences of uncertain affinity, for example by measuring their whole-rock lead isotopic compositions.

INTRODUCTION

During the last few years, Appalachian geologists have begun to explore the possibility that this orogen is partly made up of discrete terranes, added piecemeal during its long Paleozoic geologic evolution. This new way to look at orogens could change the tectonic outlook of Appalachian geology profoundly because the very idea of on-strike continuity of first-order tectonic elements is being challenged. Recent studies that treat the Appalachians as mosaics of accreted terranes include: Zen (1981, 1983), Drake and Morgan (1981), Keppie (1982), and Williams and Hatcher (1983). Stewart and Wones (1974) gave a prescient discussion of the geology in the Penobscot Bay area of coastal Maine in terms of “blocks” that show disparate stratigraphic, tectonic, plutonic, and metamorphic histories. Today these “blocks” would be called “tectonostratigraphic terranes”.

For the western North American cordillera, where the formal suggestion of piecemeal terrane accretion originated, many of the rocks
have not been involved in multiple plutonic, high-grade metamorphic, and orogenic events. The kinds of evidence used there to decipher individual accreted terranes, therefore, may not work for orogens that have gone through repeated thermal and deformational events. Can we use differences in the nature and history of the metamorphism to define and describe distinct terranes? The symposium “Metamorphic histories of Appalachian terranes: Contrasts and comparisons across possible microplate boundaries” (Geol. Soc. America, 1985) considered this challenge.

This paper inquires into the feasibility of using metamorphism in terrane analysis. I shall divide the paper into three parts. First, I review how metamorphism affects the primary evidence used to establish discrete terranes in orogenic systems. Second, I discuss the expected ranges of metamorphic grade, style, and history if different parts of a single coherent terrane are subjected to differential burial, uplift, and plutonism: Could such intra-terrane differences be as large as reasonably expectable inter-terrane differences? Finally, I suggest some research areas where metamorphic petrology and geochemistry could furnish insights on distinguishing terranes. There can be little doubt that the role of metamorphism in terrane analysis will acquire more importance as the concept of accreted terranes becomes more widely applied to older orogens, and so this seems a good time to examine our tools.

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EVIDENCE FOR ACCRETED TERRANES

Table 1 lists different kinds of evidence used to establish or to support the existence of accreted terranes at various places (to avoid an encyclopedic reference section, I will not cite the literature in this
general context). Clearly, some kinds of evidence are more definitive than others, and each kind will respond to a metamorphic imprint in its own way. Among the kinds of evidence listed, four are potentially definitive in establishing the presence of accreted terranes. By contrast, the others are useful mainly to support the hypothesis: like trained police dogs they can sniff out suspicious material but can never prove a guilty origin. The four “best” kinds of evidence are briefly discussed next.

**Faunal assemblages and affinities.**—The presence of fossils and faunae in juxtaposed coeval stratigraphic sections that show different geographic and ecological niches has been used widely to establish the mutually exotic nature of terranes in the western cordillera (for example, Monger and Ross, 1971; Silberling, 1985. Neuman and others, in press, gave a summary of Paleozoic Appalachian faunae in this context). To be sure, the environmental versus geographic significance of contrasting faunae can be argued, but advances in paleontological understanding are making this tool increasingly attractive.

**Paleolatitudes.**—Direct indications of incompatible paleolatitudes for juxtaposed rocks constitute cogent evidence of their mutually exotic relations. Paleomagnetic latitudes constitute the most commonly used evidence of this sort and, especially in conjunction with faunal disparities, have been widely accepted as a primary kind of evidence not only for the displaced nature of a terrane, but also for estimating the amount of the displacement (Jones, Silberling, and Hillhouse, 1977).

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**Table 1**

Criteria useful for recognition of terranes

| I. Primary evidence useful in establishing discrete terranes: |
| Coeval but incompatible fossils and faunal affinity |
| Inconsistent paleomagnetic latitude |
| Contrasting apposed sedimentary facies and truncated sedimentary dispersal system |
| Intercalated oceanic ophiolite, spreading-center deposits |

| II. Supporting evidence useful in corroborating discrete terranes: |
| A. Indicators of arc-trench and plate-margin environment: |
| Arc volcanism and magmatism |
| Trench melange |
| Blueschist and related rocks, especially associated with melange |

| B. Indicators of different basalts underlying suspect terranes: |
| Aeromagnetic patterns |
| Gravity patterns |
| Different deep seismic reflection patterns and crustal velocity structures |
| Distinct geochemistry of plutons, including isotope ratios |
| Distinct isotopic geochemistry of sedimentary rocks |
| Distinct ages of basement rocks |

| C. Indicators of transport of rocks: |
| Large transcurrent faults |
| Large thrust faults |
| Different metamorphic and tectonic histories |
Sedimentary regime and anatomy of sedimentary system.—By “sedimentary regime” I mean the environment of deposition of ensembles of sedimentary rocks, such as deep-sea fans, abyssal sediments on an oceanic crust, shelf sediments, deltaic sediments, or fluvialite sediments. By “anatomy” of sedimentary systems, I mean the detailed information on the sedimentary layering and other primary structures, grain-size distribution, or chemical changes in the sediments that can be related to the position of the sedimentary rocks within a depositional regime. For instance, ribbon chert with or without radiolaria or cobaltiferous manganese nodules might be telltale signs of an abyssal depositional regime, whereas coarse, well-sorted, and well-rounded conglomerate associated with marly shales, brackish water coal beds, and cross-bedded sandstones could suggest deltaic environment of sedimentation. If these two rock assemblages are in coeval sections now in direct apposition, then an inference of mutually exotic relation could be justified. Such inferences, based on contrasting sedimentary facies, are one strong argument for the reality of late Paleozoic and early Mesozoic accreted terranes in western Nevada (Speed, 1978, 1979). Conversely, if some integral part of a depositional regime is missing, then there would be valid grounds for suspecting that parts of a terrane have been decreted (Bluck, 1983, 1986; Murphy and Hutton, 1986).

Oceanic ophiolite and spreading-center deposits.—The presence of an oceanic ophiolite sequence structurally intercalated among sedimentary rock sequences of contrasting facies usually provides strong evidence that the two sequences bounding the ophiolite are mutually exotic (see Jones and others, 1980, for a deft use of this criterion). Two fault-bounded sequences separated by oceanic spreading-center deposits, possibly distinguished by such features as chimney-type sulfide deposits, could also show the mutually exotic relation of the bounding sequences, especially if these sequences show contrasting sedimentary regimes.

I consider these four sets of evidence to be the most persuasive of all those used to establish the presence of exotic terranes. The other lines of evidence included in Table 1 tend to be supportive at best, and for this reason, with but one exception, they will not be examined further. That one exception is the use of metamorphic histories as a criterion for recognizing and defining terranes: it will occupy the remainder of this study.

POSSIBLE METAMORPHIC EFFECTS ON THE PRIMARY EVIDENCE

Metamorphism tends to deform and destroy fossils, especially megafossils. True, identifiable fossils have been preserved in rocks even in the sillimanite grade (Boucot and Thompson, 1963; Boucot and others, 1972), and microfossils such as conodonts and ostracodes have increasingly been found in metamorphic rocks. Some of these fossils have even allowed provenance assignments, and others carry a record of the thermal history of the rock. Nevertheless, by and large the effect
of metamorphism is to degrade or to eliminate the usefulness of fossils in terrane analysis. Metamorphism modifies or destroys the original magnetic signatures imparted on a rock during its initial formation. This destructive effect is certainly most complete for metamorphism at or above the amphibolite facies (staurolite–garnet–bearing pelitic assemblages). To be sure, two metamorphic terranes that have cooled separately through the Curie temperatures without further deformation might preserve disparate paleomagnetic latitudes acquired during the thermal events. However, the evidence would likely be difficult to interpret. The recent realization that some apparently well-determined differences of paleolatitudes for the northern Appalachians are really artifacts (Irving and Strong, 1985; Kent and Opdyke, 1985) points to the possible risk of this tool.

The effect of metamorphism on sedimentary regimes and structures is harder to predict. Geochemical peculiarities such as manganiferous beds or coal beds might survive considerable metamorphism and might even be accentuated by it (for example, calc-silicate pods), but delicate sedimentary structures or grain size distribution that might provide clues to the sedimentary environments or to the original position of the assemblage in a sedimentary system may be expected to be degraded or destroyed. Much research remains to be done in this area.

Large oceanic ophiolite sequences appear resistant to modest amounts of metamorphism as attested by their preservation in Quebec and in western Newfoundland. However, persistent questions remain about the protoliths of numerous small ultramafic bodies that decorate the major orogens. These are now dunites, harzburgites, or their volatile-bearing equivalents: serpentinites, talc-magnesite bodies, and similar rocks. Are these tectonically dismembered oceanic ophiolites? If so, they can serve as evidence of terrane juxtaposition. Are they large olistostromes of oceanic ophiolite embedded in now-metamorphosed melanges? If so, they can still indicate former active plate-margin processes involving the ocean floor, even though the evidence is less direct. On the other hand, if they are dismembered layered mafic intrusive rocks, metamorphosed siliceous dolostones, or metamorphic segregations in a sedimentary sequence, then they cannot illuminate the problem of terranes. I will return to the problem of ultramafic bodies toward the end of this essay.

Could metamorphism play a more constructive role in terrane analysis? To answer this question, we need to examine the possible ranges of metamorphic style, age, and grade within a single terrane. In addition to careful use of field evidence to establish these limits for demonstrably coherent terranes (Geol. Soc. America, 1985), another way to gain insight is by modelling of thermal and uplift histories of rock masses.
MODEL RESULTS OF POSSIBLE INTRA-TERRANE DIFFERENCES IN METAMORPHISM

If two mutually exotic terranes, both already metamorphosed, are juxtaposed, then at least in principle we should be able to use their different histories to distinguish the terranes, whether they share a metamorphic overprint or not. If they do share an overprint, its age could provide additional useful information on the minimum age of accretion, just as an overlap stratigraphic sequence could. Unlike the deposition of an overlap sequence, however, a metamorphic overprint is apt to obscure the earlier records in terms of chronological data, mineral assemblages, or textural relations, especially if the younger event is of higher grade than one or both of the older events. Detailed studies in northwestern British Columbia (Selverstone and Hollister, 1980; Crawford and Hollister, 1982; Hollister, 1982; Crawford, Hollister, and Woodsworth, 1987), however, show that a complex thermal and tectonic history can be disentangled by using the record of polyphase metamorphism. The use of various kinds of mineral assemblage data to determine pressure and temperature of metamorphism is legion. Use of strain data on mineral inclusions (for example, Rosenfeld and Chase, 1961; Rosenfeld, 1969; Chopin, 1984), as well as of fluid inclusions (for example, Selverstone and Hollister, 1980; Sisson, ms), to determine the pressure and temperature of metamorphism and eventually to determine the pressure-temperature-time (P-T-t) paths of rocks (Spear and Selverstone, 1983; Selverstone and others, 1984: Spear and others, 1984) are among ways to decipher the history of tectonic evolution and possibly to discern mutually exotic relations.

Confident interpretation of P-T-t path differences as evidence for discrete terranes depends on knowing how P-T-t paths can vary within a single coherent burial-thermal system (which, for the present discussion, may be identified with a terrane) by virtue of the locations of rock bodies within it. Fortunately, this problem has become increasingly tractable through computer-modelling of thermal regimes of orogens by using geologically reasonable initial and boundary conditions (for example, Oxburgh and Turcotte, 1974; Wells, 1980; Brewer, 1981; England and Thompson, 1984; Chamberlain and England, 1985). Most of the existing models are one-dimensional; even so, they can provide insight on possible intra-terranne variations. Some insights on two-dimensional relations can be gained by comparison of one-dimensional results for different portions of the orogen prescribed by different initial and boundary conditions, assuming no lateral transfer of energy or mass.

Two sample calculations, based on a program written by Haugerud (1986), are presented in figures 1 and 2. In figure 1, one part of the orogen, curve A, is buried by three instantaneously emplaced thrust sheets of supracrustal material; the sheets are 6 km thick and are emplaced at 0.5 my intervals. Thermal adjustment proceeded during the thrusting interval and during a subsequent 5-my incubation period.
Uplift, balanced by erosion, at a uniform rate of 0.20 mm/yr then proceeded for 100 my, at the end of which the rock located 2 km below the pre-thrusting surface is exposed. The P–T–t path of this rock body (fig. 1) shows that the maximum temperature attained is about 370°C: presumably rocks of suitable composition would have a mineral assemblage recording conditions at the boundary of the pumpellyite-greenschist facies.

Another part of the orogen (fig. 1, curve B) is buried by five thrust sheets each 6 km thick, again instantaneously and at 0.5-my intervals. Thrusting is followed by 5 my of incubation, then uplift at a uniform rate of 0.50 mm/yr for 100 my, at the end of which the rock located 20 km below the pre-thrusting surface is exposed. The P–T–t path shows that the maximum temperature attained is about 670°C and that the rock goes through the eclogite and the upper amphibolite facies of metamorphism. Because of the duration and temperature of the heat-up cycle, the earlier, high-pressure metamorphism is not likely to be preserved (a candidate for such chance preservation may be the glaucope-omphacite schist in the Tillotson Peak area of northern Vermont, in rocks now in the kyanite grade of regional metamorphism, Laird and Albee, 1981). Extensive anatexis can be expected, and the melt could include not only granitic but even tonalitic material if suitable source rocks exist. These plutonic and metamorphic rocks can be expected to record hornblende $^{39}$Ar/$^{40}$Ar cooling ages several tens of million years younger than any amphibole that might have grown in rock mass (A).

Despite the complexities just outlined, careful comparison of cooling histories and retrograde mineral assemblages of these rock masses with model predictions may allow us to distinguish intra-terrane thermal differences from inter-terrane contrasts. A possible example of such contrasting thermal and metamorphic histories developed in the same terrane is in the northern Cascades of Washington. There, the Tonga Formation of Yeats (ms), a blueschist with greenschist overprint, is separated by the apparently local Evergreen fault from the possibly coeval Chiwaukum Schist that is in Barrovian metamorphic zones and that has undergone a complex uplift, metamorphic, and plutonic history (see Zen, in press).

As a second example, figure 2 shows the results of using five thrust sheets, whose emplacement and incubation conditions are the same as for rock mass (B), (fig. 1). The uplift and erosion rate is uniform at 0.32 mm/yr for 100 my, 87.5 my into the uplift event, however, a magma body 5 km thick, derived from partial melting in a source region between 26 to 35 km depth, is instantaneously emplaced: the top of the pluton is at a depth of 5 km. This magma is assigned a uniform temperature of 700°C (as is the 5 km of restite), corresponding to the average temperature of the source region at the moment of magma separation. As the result of the intrusion, the crust between 5- and
Fig. 1. One-dimensional uplift model. Instantaneous thrusting of sedimentary sheets, each 6-km thick, at 0.5 my intervals, followed by a 5-my incubation period. Uplift, balanced by erosion, then proceeds for 100 my. (A)—P–T–t path of a rock mass 2 km below the pre-thrust surface, buried under three thrust sheets. Erosion proceeds at 0.20 mm/yr, so that after 100 my the rock mass is exposed. (B)—P–T–t path of a rock mass 20 km below the pre-thrusting surface, buried under five thrust sheets. Erosion proceeds at 0.50 mm/yr, so that after 100 my the rock mass is exposed. Dots on the curves indicate position of the samples at 10-my intervals since beginning of uplift (right end of the horizontal line segments). Labeled lines: (1) laumontite = lawsonite + quartz + H₂O (Nitsch, 1968); (2) calcite-argonite; (Johannes and Puhan, 1971). (3) albite = jadeite + quartz (Boettcher and Wyllie, 1969); (4, 5, and 6) tonalite solidi for a H₂O-saturated melt, for a dry melt, and for a melt sufficiently hydrous as to allow hornblende and biotite to crystallize respectively (Wyllie, 1977); (7) 8-kb melting interval for H₂O-saturated synthetic granodiorite (Naney, 1983) from which epidote crystallized at T < ~700°C; (8 and 9) wet and dry solidi for pelite melting (England and Thompson, 1984); (10) the stability fields of the polymorphs of aluminum silicate minerals (Holdaway, 1971). The argon-blocking temperature ranges for hornblende and for biotite are shown along the top margin of the diagram.

Modelling parameters used: Thermal conductivity, 2.25 W·m⁻¹·K⁻¹. Density, 2780 kg/m³. Heat capacity, 900 J·K⁻¹·kg⁻¹. Heat generation, 2 μW·m⁻³, restricted to upper 15 km of original crust (and overthrust material), and zero elsewhere. Surface temperature 0°C. Basal flux, constant at 50 mW·m⁻². Lower model depth, 150 km. The metamorphic facies are indicated.
Fig. 2. Effect of instantaneous emplacement of anatetic magma within the crust. Five thrust sheets of sedimentary material are emplaced, each 6 km thick, at 0.5-my intervals, followed by 5 my of incubation and uniform erosion and uplift at 0.32 mm/yr for 100 my. 87.5 my into the uplift cycle, 50 percent of the material between 26 and 35 km (originally between 24 and 33 km) instantaneously ascended as magma to just beneath the 5-km level (originally 3 km beneath the surface), at a uniform temperature of 700°C; the remaining 5 km of restite, at the same temperature, settles to depth between 31 and 35 km, and the crust between 5 and 26 km is depressed instantaneously to levels between 10 and 31 km. The pre-thrusting depths of the monitored P–T–t paths are given at the left end of the curves. Dots along the curves mark 10 my time lapses since uplift begins. The deepest monitored path shows only a brief increase in cooling rate. The two intermediate paths show loops caused by the crustal depression. The shallowest path shows only a thermal spike that lasts between 0.5 to 1 my during which andalusite could form in the contact aureole; complete re-equilibration occurs about 2.5 my after intrusion. The solidus of the pelitic minimum melt (curve 8) and the stability fields of the aluminum silicate polymorphs (curve 10) are those of figure 1, here shown for reference. Other modelling parameters same as for figure 1, except that the lower model depth is 100 km. The effect of latent heat of fusion is ignored; the correction on the thermal profile is less than 20°C at the time of intrusion.
25-km depth is depressed instantaneously and uniformly by 5 km and lies above the restite (which presumably will have somewhat higher values of seismic velocities than the original rocks). Below that level, the original rock masses would be undisturbed by the event.

At the level of intrusion, conditions are right for development of andalusite-bearing assemblages, regionally or around the pluton, for a period of a few hundred thousand years (fig. 2). Such assemblages would be superimposed on pre-existing kyanite schists, and any preexisting hornblende would yield a complex cooling history (for a possible example in the northern Appalachians, see Woodland, 1963). Buchan-type metamorphism involving prograde andalusite and sillimanite, such as in central Maine and recently modelled by Lux and others (1986), by analogy, could be derived by shallow-level intrusion of anatexic melts, for example into rock mass (A) of figure 1, 70 to 80 my into the uplift history.

Three kinds of P–T–t paths are shown in figure 2: merely a minor inflection for the deepest curve; a sharp thermal spike for the shallowest curve; and distinct P–T loops for the two intermediate rocks between the levels of the source region and the pluton. Rocks associated with these curves can be expected to exhibit hornblende $^{59}\text{Ar}/^{40}\text{Ar}$ ages that differ by tens of million years and show different complexities: yet they resulted from a single thermal event within a single terrane.

These two examples illustrate the possible ranges of intra-terrane metamorphic and plutonic history under geologically reasonable conditions. Such contrasts can be expected to be enhanced by intra-terrane high angle faulting commonly found in orogens. What kind of contrast, indeed, will be sufficient to justify an inference of terrane juxtaposition? Unfortunately, such calibration either does not exist or has not yet been recognized. Until we have such a calibration, use of metamorphism as a primary tool in terrane definition must be viewed with benign suspicion.

**METAMORPHIC ROCKS AND TERRANE ANALYSIS**

The preceding discussion seems pessimistic. However, metamorphic rocks can furnish additional helpful constraints to terrane analysis, and I will suggest several possibly profitable directions of research.

*Improve methods in P–T–t path reconstructions.*—The possibility of reconstructing P–T–t paths for metamorphic rocks opens up new ways to understand the complex history of metamorphism of orogens, especially old orogens. Use of the method requires knowing the thermodynamic variance of the mineral assemblages in question; confident reconstruction of the partly destroyed pre-existing mineral assemblages is not always feasible, and refinements of this tool are desirable (Selverstone and others, 1984; Spear and Rumble, 1986). In addition to improving our ability to interpret mineral and rock textures and relating these features to geochronological data, improved experimental phase-
equilibrium and thermochemical data, especially of solid solution systems, are needed. In addition to recording the nature of any retrograde mineral assemblage, petrologists should provide mineral contact textures for microprobe-analyzed samples so the information can be used for P-T-t path studies. Knowing the ages of the individual stages along the P-T-t path is important; here, recent developments in microtechniques for geochronology (for example, Sutter and Hartung, 1984; Mattinson, 1985) are promising. Haugerud and Zen (in press) recently reviewed the subject.

**Improved models.**—Modelling efforts have provided us with new insights on the thermal structures of burial systems, and continued effort in this direction is needed. Two-dimensional models can approximate nature better because they allow non-horizontal geometry as well as lateral heat flow and mass transfer (Jaupart and Provost, 1985). Another important parameter to model is advective heat transport, both by magma and by hydrothermal systems (Hugerud and Zen, in press). Decompression of rock bodies by methods other than direct erosion can be important: for example, crustal thinning by listric faulting can cause pressure decrease and concomitant temperature increase. All the simple thermal models of which I know predict extensive retrograde metamorphism: how do we quench in the prograde metamorphism, as rocks indeed commonly do? Draper and Bone (1981) discussed the thermal implications of preservation of blueschists: could it be that some instances of lack of retrograde metamorphism imply quenching by abrupt thermal events in a terrane and thus could be a useful earmark?

**Ophiolites.**—Earlier, I suggested that an ability to recognize oceanic ophiolites in ancient orogens could go far in the delineation of terranes. Need for this ability is particularly acute for those small enigmatic ultramafic bodies that typically dot orogens. Anhydrous ultramafic bodies do not necessarily provide samples of the protolith: Evans and Trommsdorff (1974) and Frost (1975), among others, described dunites and harzburgites in the Alps and in the northern Cascades that are metamorphosed serpentinites; Carpenter and Phyfer (1969) and Lipin (1984) discussed the probable metamorphic origin of some anhydrous alpine ultramafic bodies in the southern Appalachians. Because the original mineralogy and texture of these rocks are commonly obliterated, these features in general cannot be used to infer the nature of the protolith, and we need alternative characteristics that are relatively immune to metamorphism and deformation.

**Application of geochemical tracers.**—Geochemical and isotopic tracers have been used successfully in many areas to determine the affinity of protoliths. For the ultramafic bodies, their rare-earth-element and isotopic abundances (for example, the neodymium-samarium systematics: Shaw and Wasserburg, 1984) can help, but the method addresses the question of the nature of the source material for the mafic magma rather than the tectonic setting of the igneous rock. Use of relative abundances of the platinium group elements (Page and others, 1980:
Page, Cassard, and Hafty, 1982) is a promising means to discriminate different types of ultramafic rocks that is already providing useful clues for some of the enigmatic rocks in the southern Appalachian Piedmont (Lipin, 1984).

Ayuso (1986) showed that, for the plutons of Maine, the isotope ratios of lead in feldspar depend on the location in the orogen and thus presumably reflect different source terranes. Ayuso found that the boundaries of these terranes coincide with those based on exposed-bedrock distributions (Zen, 1983; Stewart and others, in preparation). LeHuray and Slack (1985) and Swinden and Thorp (1984), using isotope ratios of lead in galena, similarly found a correlation between sample location and proposed terrane boundaries in the northern Appalachians, although the feldspar and galena leads do not give consistent patterns of isotope ratios.

The isotopic ratios of whole-rock lead of sedimentary sequences and their metamorphic equivalents might yield useful information. Widely distributed, medium- to fine-grained, immature sedimentary units should be efficient mixers of the source areas and thus not necessarily reflect the idiosyncrasy of some individual unit of source rock. If the source areas are distinct terranes and have different lead-isotope signatures, as Ayuso’s data suggest, then coeval sedimentary rocks derived from these source terranes should carry distinctive lead isotope signatures. Metamorphism might create complications by resetting the growth curves for the Pb–U and Pb–Th systems, but whether such complications are fatal remains to be seen. Here, metamorphic petrology could provide the insight to ensure that the data can be interpreted in a meaningful way.

References
and the effect of metamorphism


