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Computational Geology 20

Rocks at the Intersection

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Topics this issue-

Mathematics: Complement, intersection, union; partitions.
Geology: Classification of rocks; igneous, sedimentary and metamorphic.

Prerequisites: CG-18, "Definition and the Concept of Set," Nov. 2001; CG-19, "Classification and the Combination of Sets, Jan., 2002.

Introduction

This is the third column in a series on sets and geological terminology, and the second on terms used to classify rocks. I will pick up on a topic that was only lightly touched in the last column: "classifications obtained by sorting." In such classifications, one selects samples from the universal set, sorts them into different classes, and labels the classes from some definitive attribute, all the while not knowing what will be coming next out of the universal set. The point of this column is that this process does not partition the universal set in the way that one might think. A partition, recall, is a collection of mutually exclusive (disjoint) sets whose union equals (exhausts) the universal set.

The point is easy to illustrate by thinking of sorting socks. Let's say several blue socks present themselves, and then several white socks. The sock-sorter might think of two classes: one defined as blue, the other defined as white. Obviously, though, blue and white are not mutually exclusive in socks. The next sock pulled from the universal set might be a blue-and-white plaid – i.e., it would be in the intersection of blue and white. Nor do blue and white exhaust the possible colors. The next sock might be lacking both blue and white – i.e., it would be in the complement of the union of blue and white. Thus the two attributes blue and white partition socks into four sets: socks that are totally blue, socks that are totally white, socks that are partly blue and partly white, and socks that have no blue and no white.

In the early days, classifying rocks was in some ways like sorting socks – geologists had no foreknowledge of the universal set. They discovered, and they named. And now in hindsight, we get this terrific line from Shand (1949, p.243-244, in Raymond, 2002, p. 33), referring to igneous rocks:

> … the witless practice of giving a new name to every rock that is slightly different from any rock seen before and thus to extend indefinitely the list of 'specific' names which already contains over six hundred items and includes such gems as katzenbuckelite and leeuwfonteinite, anabohitsite and sviatoynossite, bogusite and bugite.

The context of the quotation in Raymond's book is a statement concerning problems that have "confounded attempts at igneous rock classification." Thus (Raymond, 2002, p.33):

> A primary problem is that nature contains a continuum of rock types that we attempt to artificially subdivide into groups. Rock names provide another problem, because many commonly used names were applied to rocks before classifications were developed. Consequently, names were not created in a systematic way. Few geologists are willing to abandon the traditional names, yet there is no consensus for redefining traditional terms.

The same is more or less true of the most traditional, not to mention most basic, of names for rock classes – igneous, metamorphic, and sedimentary. As geologists have learned more about geologic processes, the meanings of these terms have evolved. A certain amount of rethinking is always good, of course, but there is also a tendency in classifications obtained by sorting to contort and/or restrict the definitions to accommodate the notion that the classes must be mutually exclusive and comprehensive. The purpose of this column is to point out that there is an alternative to contorting and restricting the definitions to fit new information: simply admit that the classes may overlap each other and may underfill the domain.

A Reverse-Rorschach Test

Geologists are visual people. Many geology professors ask students to draw diagrams for answers to short-answer exam questions. Many of these questions amount to short reverse-Rorschach tests. What picture comes to mind when you think of a *subduction zone*? What image represents your concept of the *rock cycle*?

The theme of this column can be represented by a similar question: What diagram conveys your view of how igneous, sedimentary and igneous occurs within the domain, rocks?

To see what I am getting at, consider the following multiple-choice questions concerning a hand sample of some random rock. Call the rock sample *x*.

1. If *x* is a sedimentary rock, then it is not an igneous rock.
    - A. The statement is true.
    - B. There may be cases where the statement is false.

2. If *x* is neither a sedimentary rock nor an igneous rock, then it is a metamorphic rock.
    - A. The statement is true.
    - B. There may be cases where the statement is false.

3. If *x* is not a sedimentary rock, then it is either an igneous rock or a metamorphic rock.
    - A. The statement is true.
    - B. There may be cases where the statement is false.

If your answers to these three questions are all A, then you think of the terms igneous, sedimentary, and metamorphic as forming a three-fold partition of rocks. In other words, in your concept, the terms *subdivide* the domain such that every rock sample is in one and only one class. Your picture for it might be like Figure 1.

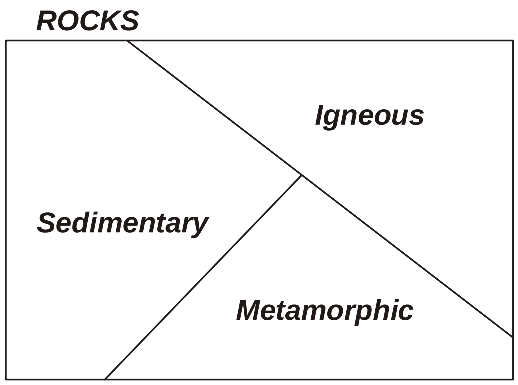

Figure 1. Three sets forming a three-fold partition of rocks.

My point is that that is the way geologists tend to think of igneous, sedimentary, and metamorphic rocks. Certainly, that is the way we teach it to students. But it doesn't have to be that way. Defining igneous, sedimentary, and metamorphic is not like defining boulders, cobbles, pebbles, and so on. In the latter case – definition of particle size – a partition is *designed* by subdividing a scale. In the case of igneous, sedimentary, and metamorphic, the classification is obtained by: well, this rock formed this way, and that rock formed that way, and, lets' see, this third rock formed this third way. Why can't there be a fourth way? Why can't there be rocks that formed in part this way and in part that way? If you think those questions have merit, then your picture for the classification of rocks by the terms igneous, sedimentary and metamorphic might be like the Venn diagram of Figure 2.

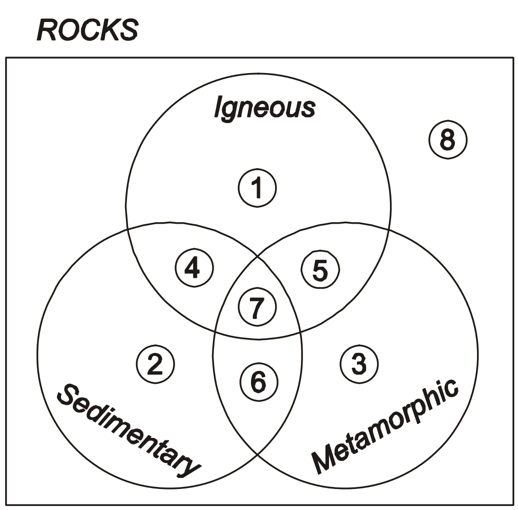

Figure 2. Three sets forming an eight-fold partition of rocks.

To elaborate on Figure 2, three definitions result in eight potential classes. More specifically, let R be the domain, rocks. Let R_I be the set within R resulting from the definition of igneous; let R_S be the set within R resulting from the definition of sedimentary; and let R_M be the set within R resulting from the definition of metamorphic. Then there are potentially eight separate classes of rocks:

1. $R_I - R_S - R_M$, rocks that are igneous only.
2. $R_S - R_I - R_M$, rocks that are sedimentary only.
3. $R_M - R_I - R_S$, rocks that are metamorphic only.
4. $(R_I \cap R_S) - R_M$, rocks that in some way are both igneous and sedimentary, but not metamorphic.
5. $(R_I \cap R_M) - R_S$, rocks that in some way are both igneous and metamorphic, but not sedimentary.
6. $(R_S \cap R_M) - R_I$, rocks that in some way are both sedimentary and metamorphic, but not igneous.
7. $R_I \cap R_S \cap R_M$, rocks that in some way are igneous, sedimentary, and metamorphic.
8. $R - (R_I \cup R_S \cup R_M)$, rocks that are neither igneous, sedimentary or metamorphic.

The first three sets are straightforward. The first, the "purely" igneous rocks include such rocks as basalt, andesite, and intrusive granites. The second, the "purely" sedimentary rocks include such stalwarts as conglomerate, shale and limestone. The third, the "purely" metamorphic rocks include mylonite (cataclastic metamorphism), slate and schist (dynamothermal metamorphism), and hornfels (contact metamorphism). What rocks, if any, occur in the other five sets? The rest of this column offers some examples.

Hybrids and Mixtures

Again, let x be a sample of rock. The sample can range from a hand sample to an outcrop. There are at least two ways that x can lie in an intersection of igneous, sedimentary and/or metamorphic. First, there are hybrids, where the constituents of x formed by a combination of processes. Second, there are mixtures, where some constituents formed by one process and some constituents formed by another – to the extent that one cannot say that the rock as a whole is one genetic type or the other. (This last part means that I do not intend to count a conglomerate composed of volcanic pebbles as a mixture; the rock as a whole is sedimentary no matter what the origin is of the clasts. Also, I do not intend to include outcrop-size occurrences where one rock is distinctly in contact with another, as in the case, for example, of a nonconformity.)

It is important to make a distinction at the outset. If we say that x is in an intersection, then we are saying that we believe that the sample is *both* one thing *and* the other. We are not saying that, gee, we really don't know – maybe it is this (and not that), or that (and not this), or maybe even both this and that. If we have that sort of uncertainty as to what x is, then we are saying that x is in the union of this and that, not in the intersection. Saying that x is in the intersection is much stronger than saying it is in the union.

Getting started. We need now some specific definitions of igneous, metamorphic and sedimentary. There is no more authoritative source than the AGI *Glossary of Geology* (Jackson, 1997):

> **igneous**. Said of a rock or mineral that solidified from molten or partly molten material, i.e., from a magma; also, applied to processes leading to, related to, or resulting from the formation of such rocks. Igneous rocks constitute one of the three main classes into which rocks are divided, the others being metamorphic and sedimentary. (p. 318)
>
> **metamorphic rock**. (a) In its original usage (Lyell, 1833), the group of gneisses and crystalline schists. (b) In current usage, any rock derived from pre-existing rocks by mineralogical, chemical, and/or structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment, generally at depth in the Earth's crust (p. 403).
>
> **sedimentary rock**. (a) a rock resulting from the consolidation of loose sediment that has accumulated in layers; e.g., a clastic rock (such as conglomerate or tillite) consisting of mechanically formed fragments of older rock transported from its source and deposited in water or from air or ice; or a chemical rock (such as rock salt or gypsum) formed by precipitation from solution; or an organic rock (such as certain limestones) consisting of the remains or secretions of plants and animals…. (b) Less restrictedly, a general term for any sedimentary material, unconsolidated or consolidated. This usage should be avoided. (p. 579)

Intersection of igneous and sedimentary. One example of $(R_I \cap R_S) - R_M$ is easy: let x be an unmetamorphosed ash-fall tuff. For that matter, let x be any unmetamorphosed pyroclastic rock, i.e., composed of material "formed by volcanic explosion or aerial expulsion from a volcanic vent" (Jackson, 1997, p. 521). Although some of this material was solid when it was blown out of the volcano, much of it was magma that was blown out and then crystallized in transit to the site of deposition. This material is hybrid: igneous because it crystallized from magma; sedimentary because it accumulated by gravitational settling.

Pyroclastic rocks illustrate the difficulties of classifying rocks that lie in an intersection. Many books that deal with all three types of rocks discuss pyroclastic material in the sections dealing with igneous rocks (e.g., Skinner and Porter, 2000; Ehlers and Blatt, 1982; Raymond, 2002). Books dealing with sedimentary rocks, on the other hand, commonly include pyroclastic rocks. For example, the classic reference by Pettijohn (1972) includes pyroclastic material in its chapter on volcaniclastic sediments, saying "volcaniclastic materials include pyroclastic debris (as well as) deposits derived from volcanic source rocks by ordinary processes of weathering" (p. 299).

A second hybrid lying in $(R_I \cap R_S) - R_M$, is unmetamorphosed cumulate-texture gabbro, composed largely of early-formed crystals that have settled to the bottom of the magma chamber. The context, the crystallization of the settled particles, and the crystallization of the material from the intercumulus liquid all certainly make the rock igneous, but the gravitational settling is a sedimentary process. Some examples even have sedimentary structures such as cross-bedding, channeling, grading, and stratification

(Raymond, 2002, p. 170). One might call the rock a sedimentary gabbro. It is not an oxymoron.

A third example in $(R_I \cap R_S) - R_M$ is not included in any petrology book I know of. Its context and description is given on the "What is permafrost?" Web page of the Geological Survey of Canada:

> Permafrost is defined … as soil or rock that remains below 0°C throughout the year, and forms when the ground cools sufficiently in winter to produce a frozen layer that persists throughout the following summer….
>
> At temperatures below 0°C almost all soil moisture occurs in the form of ground ice. …
>
> Ground ice occurs in two main forms, as structure-forming ice, bonding the enclosing sediments, and as large bodies of more or less pure ice. The structure-forming ice comprises segregated ice, intrusive ice, reticulate vein ice, ice crystals, and icy coatings on soil particles. The large bodies of more or less pure ice, which exist mainly in the upper part of the ground, occur as pingo cores, massive icy beds, and ice wedges.

This GSC Web page includes a photograph of a sediment core showing reticulated ice. Let *x* be that sample. It is a rock consisting of sedimentary material cemented by igneous material.

For the last example, I am admittedly taking an expansive view of "igneous" – leaving out the part that says "i.e., magma" and focussing on the part that says "crystallized from molten material."

Intersection of igneous and metamorphic. How about serpentinized peridotites as a source of rock samples falling into $(R_I \cap R_M) - R_S$? "Peridotite" refers to a "coarse-grained plutonic rock composed chiefly of olivine with or without other mafic minerals such as pyroxenes, amphiboles, or micas, and containing little or no feldspar" (Jackson, 1997, p. 477). In petrology books, therefore, peridotites are discussed in the chapters on igneous rocks. But the rocks – as they occur in the crust – are revisited in the chapters on metamorphic rocks. Thus, according to Raymond (2002, p. 647),

> Ultramafic rocks are prone to low-temperature metamorphism and alteration. This is the case, because their constituent high P-T phases, at near-surface and low-temperature conditions are far from their fields of stability. In addition, mantle rocks are rather dry, and the upper levels of the crust are generally permeated with water, which readily combines with the anhydrous phases of the mantle rocks to produce new hydrous phases….
>
> … (B)ecause (serpentine minerals) are the dominant phase, comprising more than 90% of the modes of most ultramafic rocks equilibrated at temperatures below about 500o C, and because serpentine is a nearly ubiquitous constituent of crustal ultramafic rocks, … the processes of serpentinization warrant further comment.

As I read this, it would seem that many of the samples labeled periodotite in petrology labs would contain at least some serpentine, which would make the rock a mixture of igneous and metamorphic constituents. Let *x* be one of those samples. Indeed, let *x* be the sample shown in the photomicrograph of peridotite in Ehlers and Blatt (1982, Fig. 4-18), which, the caption says, shows a large, partly altered olivine grain surrounded by a fine-grained aggregate including the serpentine minerals, antigorite and chrysotile.

Serpentinites are considered as metamorphic rocks by Raymond (2002). Ehlers and Blatt (1982) give the following definition:

> *Serpentinite*: A rock consisting almost entirely of serpentine, derived from alteration of preexisting olivine and pyroxene.

Interestingly, Ehlers and Blatt give the definition twice, once in a chapter on igneous rocks (p. 110), and again in a chapter on metamorphic rocks (p. 516). This double listing is completely consistent with what they have to say about the terms igneous, metamorphic and sedimentary in their introductory chapter (Ehlers and Blatt, 1982, p. 3):

> This fundamental classification scheme, as is true of all human classification schemes, contains a flaw. Nature is a continuum; it is not segregated into discrete parts for our convenience. Hence, borderline or transitional rocks exist and are thrown into one or another of the three groups because of historical precedence or the whim of the classifier. For example, volcanic tuffs are rocks that originate in volcanoes. After explosive ejection as fragments into the atmosphere, they settle either on land surfaces or in water. If they settle into layers, should they then be classified as sedimentary? In most classification schemes, they are classified as igneous. A second example is the rock serpentinite…. This material begins its history in many instances as a molten silicate rock that cools to produce a crystalline aggregate of olivine and pyroxene. Such material would of course be classified as igneous. However, during cooling, water vapor reacts with the previously formed crystalline aggregate, converting much of it into serpentine, which implies that the rock should now be classified as metamorphic. Although there are some questionable types of rocks, the general threefold subdivision is satisfactory, well accepted by most geologists, and shall be used here.

(The point of this essay is that we do not have to accept that we must make a choice. For rocks like tuffs and serpentinites, it is more appropriate to say both, rather than one type or another.)

A variation on the theme illustrated by serpentinite is kimberlite, an ultramafic igneous rock (Jackson, 1997, p. 349) composed of olivine and phlogopite phenocrysts in a groundmass containing metamorphic serpentine. According to Ehlers and Blatt (1982), the olivine is commonly converted to serpentine and the phlogopite is commonly converted to chlorite. Those authors include kimberlite with peridotite in the list of “some well-recognized igneous rocks (that) are commonly found in a highly altered state” where “the alteration is related to … origin, rather than to later weathering processes” (Ehlers and Blatt, p. 110).

The classic example of a mixed rock, of course, is migmatite – which means “mixed rock.” Here is the pertinent information (Raymond, 2002, p. 564 and p. 571).:

> Migmatites are masses of crystalline, mixed rocks, consisting of various proportions of dark, ferromagnesian mineral-rich rock and light quartz- or

> feldspar-rich rock, that occur in medium- to high-grade metamorphic terranes.… The light-shaded rock is referred to as the leucosome, whereas the dark-shaded rock is referred to as the melanosome….
>
> Various types of migmatites are recognized on the basis of the structural character of the leucosome-melanosome mixtures. Where hydrous fluids are available and temperatures exceed the minimum melting temperature of wet granitoid rocks, the low melting (granitoid) fraction of the rocks will melt, coalesce, and migrate as a magma, crystallizing to form a light-colored, granitoid leucosome interlayed or intermixed with a dark-colored, refractory melanosome…..

Let x be a sample of one of these products of partial melting (anatexis). The leucosome material is igneous; the melanosome material is metamorphic. The sample is an element of $(R_I \cap R_M) - R_S$.

Intersection of sedimentary and metamorphic. $R_S \cap R_M$ forces the question of diagenesis (by definition, a sedimentary process) vs. metamorphism. The *Glossary* definition of diagenesis is (Jackson, 1997, p. 174):

> **diagenesis** [sed] All the chemical, physical, and biologic changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism…. It embraces those processes (such as compaction, cementation, reworking, authigenesis, replacement, crystallization, leaching, hydration, bacterial action, and formation of concretions) that occur under conditions of pressure (up to 1 kb) and temperature (maximum range of 100°C to 300°C) that are normal to the surficial or outer part of the Earth's crust; and it may include changes occurring after lithification under the same conditions of temperature and pressure…. There is no universally accepted definition of the term, and no delimitation (such as the boundary with metamorphism)….

And the *Glossary* definition of metamorphism is (Jackson, 1997, p. 403):

> **metamorphism**. The mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions which have generally been imposed at depth below the surface zones of weathering and cementation, and which differ from the conditions under which the rocks in question originated….

As is well known, there is room for overlap in those definitions – except for the decree that diagenesis excludes metamorphism (and weathering, for that matter).

For some detail about the potential for overlap, we can look to Raymond (2002, p. 495):

> By definition, the conditions at the beginning of metamorphism must exceed the surface conditions, which lie in the range (of P between 1 bar and 1 kb, and T between < 0°C and 60°C)…. Review of the P-T conditions of diagenesis reveals that they overlap with those of the lower limits of metamorphism. This is possible because of variations in rock and fluid phase compositions and in temperature. Diagenetic minerals can form at depths of burial that, given

> different bulk rock or fluid phase compositions or temperature, would yield metamorphic minerals. Consequently, the lower limit of metamorphism (in P-T space) is a broad boundary zone.

Another corollary would be that some parts of a heterogeneous rock body would be more susceptible to the beginning of metamorphism than others. Specifically recrystallization varies with grain size (Raymond, 2002, p. 480-481):

> …. Metamorphism will involve breaking and reforming of bonds, heterogeneous nucleation, diffiusion of ions to the newly nucleated sites, and grain growth. These changes allow the rock system to progress towards a state of lower free energy. Rocks with large amounts of grain surface area are the most susceptible to recrystallization. these would include rocks with fine grain size, irregular grain shapes, or large porosities. Recrystallization promotes a reduction in surface free energy by reducing the amount of surface.

So one might expect heterogeneity in the beginning of metamorphism at the hand-sample scale as well.

A classic example is graywacke, a sedimentary rock (sandstone) discussed in the sedimentary chapters of Raymond (2002) and books about sedimentary rocks (e.g., Pettijohn, 1975). Graywacke is notorious for its matrix, the fine-grained material between the sand grains. Here's the story on the matrix (Pettijohn, 1975, p. 229):

> …. Matrix can be produced in more than one way…. We may have protomatrix, orthomatrix, epimatrix, and pseudomatric; the first is trapped detrital clay, the second is recrystallized material, the third is the product of diagenetic alteration of sand-sized grains, and the fourth is a result of deformation and squashing of soft pelitic fragments. Although all are possible, the matrix of most older graywackes seems to be epimatrix, the result of deep buiral and low-grade metamorphism or high-grade diagenesis….

Regarding the rock itself (Pettijohn, 1975, p. 225):

> Under the microscope graywacke has the appearance of a microbreccia made of sharp, angular, sliverlike quartz, together with angular feldspar and rock particles, embedded in a paste which in some examples equals or exceeds the volume of the larger detrital grains…. This paste or matrix is a microcrystalline aggregate of quartz, feldspar, chlorite, and sericite and is, in places, replaced by patchy carbonate…. In some graywackes there may be an alignment of the folia of sericite and chlorite, an alignment which is an incipient schistosity.

The mention of chlorite, sericite, patchy carbonate and incipient foliation sounds like metamorphism. Why not just say that such graywackes are sedimentary rocks that, at the same time, exhibit selective metamorphism? If x were a sample of that kind of rock, then $x \in (R_S \cap R_M) - R_I$.

Intersection of igneous, sedimentary and metamorphic. Geologists now take seriously processes that years ago were considered fanciful. Impact geology is now a

major line of research. In contrast, in 1891, G.K. Gilbert, then Chief Geologist of the U.S. Geological Survey, and one of America's most insightful geologists ever, concluded that Meteor Crater (then Coon Buttes) near Winslow AZ is a "cryptovolcanic structure." Today, a review of terrestrial impact melting starts with this (Dressler and Reimold, 2001, p. 206):
:

> Over the last 30 years, asteroid and comet impact has become an accepted geological process within the wider geoscience community, especially after the spectacular impacts of the fragments of comet Shoemaker-Levy 9 into the atmosphere of Jupiter in July 1994 was witnessed and imaged by numerous astronomers with land-based telescopes and the Hubble Space Telescope…. The recognition of the Chicxulub (Mexico) impact as the 65-Ma-old KT boundary event responsible for a biological mass extinction event opened the eyes of the geoscience community and brought impact research into the mainstream of earth science.

According to that review, some 165 impact structures have already been recognized on Earth.

Here are some of the words used to label rocks and rock bodies that are now part of impact geology:

> **suevite** (Jackson, 1997, p. 637): Polymict impact breccia with clastic matrix containing lithic and mineral clasts in various stages of shock metamorphism, including cogenetic impact melt particles, which are in a glassy or crystallized state…. The term was originally applied to material from the Ries basin, Germany, but is now used to designate similar brecciated material (impactites) found at other meteorite impact structures.
>
> **fallback breccia** (Jackson, 1997, p. 226): An allochthonous breccia composed of fallback located within an impact or explosion crater.
>
> **fallback** (Jackson 1997, p. 226): Fragmental material ejected from an impact or explosion crater during formation and redeposited within, and partly filling, the true crater immediately after formation. It includes slide-block deposits, talus, and aerially transported material.
>
> **fallout breccia** (Jackson, 1997, p.227): An allotchthonous breccia composed of fallout from a crater. It is generally one of the last ejecta units to be deposited, and it characteristically contains small amounts of glass fragments and a limited range of fragment sizes.
>
> **fallout** [impact] (Jackson, 1997, p.227): Fragmental material ejected from an impact or explosion crater during formation and redeposited in and around the crater. It may have undergone considerable atmospheric sorting before deposition.
>
> **throwout** (Jackson, 1997, p. 664): Fragmental material ejected from a crater during formation and redeposited on or outside the crater lip.

Allochthonous breccia, ejecta, redeposition, atmospheric sorting, talus – these speak to sedimentary processes and products. There are also impact-melt particles and glass (igneous), and shock-produced phases and fabrics (metamorphic) – all part of the same rock. In the same way that samples of pyroclastic rocks are members of $R_S \cap R_I$, at least some samples of impact breccias are members of $R_S \cap R_I \cap R_M$. For details of these rocks that have everything, see Dressler and Reimold (2001) and references therein, especially Engelhardt (1990, 1997).

Complement of the Union

Let x be a sample of bull quartz from a quartz vein. Here is relevant information about veins (Raymond, 2002, p. 476):

> Veins are tabular joint or fault fillings composed of one or more minerals…. The distinction between veins and dikes is somewhat arbitrary, but the term vein tends to be applied to tabular bodies that are monomineralic, binimineralic, or contain ore minerals, whereas the term dike is used for igneous rock types crystallized from magma or magmatic vapor phases. Veins form where fluids penetrate a fracture and precipitate minerals.

So, they are like dikes, but they are not (igneous) dikes because the minerals are precipitated from fluids rather than crystallized (frozen) from magma; i.e., the rock is not igneous. The rock is not sedimentary, because it is not formed from sediments. It is not metamorphic because it did not form from pre-existing rocks (I'm talking about the vein itself, not the altered wall rock that may be present); rather, it formed in the forced-apart space between pre-existing rocks. The rock is a "none-of-the-above" rock, $R - (R_I \cup R_S \cup R_M)$.

One can perhaps wiggle out of it by appealing to hydrothermal metamorphism:

> **hydrothermal metamorphism** (Jackson, 1997, p. 311): A local type of metamorphism caused by the percolation of hot solutions or gases through fractures, causing mineralogic changes in the neighboring rock.

Well, I can understand saying that the altered wall rock is an example of hydrothermal metamorphism, but I don't see it for the rock that formed within the crack. I think that would be a case of contorting the definition (of metamorphism) to preserve the notion that sedimentary, metamorphic, and igneous produce are three sets that exhaust the possibilities for rocks. I mean, quartz from a quartz vein has to be something, so let's stretch metamorphism and make it fit there.

A Final Distinction

The discussion has centered on a sample x. I have offered examples of x that plot in the intersection of two or more genetic classes. That amounts to saying that the particular x is a member of each of the intersecting classes. That is not the same thing as saying that the rock type of which x is a sample is a subset of both of those classes.

As an example, take the sedimentary gabbro in $R_I \cap R_S$. Such gabbros are in some ways igneous and in one way sedimentary. Some gabbros, on the other hand, are in no way sedimentary (noncumulate gabbros); samples of such rocks are members of $R_I - R_S - R_M$ or, if partially metamorphosed, $(R_I \cap R_M) - R_S$. No gabbros are in no way igneous; that is no samples of gabbro are members of $R_S - R_I - R_M$. Thus all gabbros will plot in either $R_I \cap R_S$ or $R_I - R_S - R_M$ or $(R_I \cap R_M) - R_S$ (i.e., fields 4, 7, 1 or 5 of Fig. 2).

Gabbros, therefore, are a subset of igneous rocks; they are not a subset of sedimentary rocks.

Similarly migmatites are a subset of metamorphic rocks. According to Raymond (2002), there are four main proposals for the formation of migmatites: anatexis (the most likely), magmatic injection, metasomatism (granitization), and metamorphic differentiation. In all four cases, the melanosome material is metamorphic. In the first two, the leucosome material is igneous; in the last two, the leucosome material is metamorphic. Thus, the first two genetic types of migmatite belong in $(R_I \cap R_M) - R_S$ (field 5 of Fig. 2), and the second two genetic types belong in $R_M - R_I - R_S$ (field 3). No migmatites belong in $R_I - R_S - R_M$ (field 1). This puts all migmatites in R_M, but one cannot say that all migmatites are in R_I, although some of them are. Thus migmatites are a subset of R_M and not a subset of R_I.

Pyroclastic rocks, on the other hand, all belong in $R_I \cap R_S$ (field 4 and, if slightly metamorphosed, field 7). No pyroclastics are completely lacking of a sedimentation story; i.e., none plot in $R_I - R_S - R_M$ (field 1). Similarly, no pyroclastics plot in $R_S - R_I - R_M$ (field 2) (although nonpyroclastic volcaniclastic sediments do). Therefore pyroclastic rocks are a subset of $R_I \cap R_S$. This means that pyroclastic rocks are a subset of sedimentary rocks (R_S), *and* they are a subset of igneous rocks (R_I).

At the other extreme, there are some rock types that are not a subset of any of the big three genetic classes. For example, consider ice. Lake ice, the ice of ice wedges, and the ice in the core of pingos are all purely igneous and belong in $R_I - R_S - R_M$ (field 1) Glacial ice formed by recrystallization of snow is metamorphic and belongs in either $R_M - R_I - R_S$ (field 3) or $(R_S \cap R_M) - R_I$ (field 6) depending on how you look at it. This means that geological ice is not a subset of R_I, R_M, or R_S.

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References Cited

Dressler, B.O. and Reimold, W.U., 2001, Terrestrial impact melt rocks and glasses: Earth Science Reviews, v. 56(1-4), p. 205-284.

Ehlers, E.G. and Blatt, H., 1982, Petrology, igneous, sedimentary and metamorphic: San Francisco, Freeman, 732 p.

Englehardt, W. von, 1990, Distribution, petrography and shock metamorphism of the ejecta of the Ries crater in German -- a review: Tectonophysics, v. 171, p. 259-273.

Englehardt, W. von, 1997, Suevite breccia of the Ries impact crater, Germany: petrography, chemistry and shock metamorphism of crystalline clast: Meteoritics and Planetary Science, v. 32, p. 545-554.

Jackson, J.A., 1997, Glossary of Geology, 4th edition, Alexandria, American Geological Institute, 769 p.

Pedttijohn, F.J., 1975, Sedimentary rocks, 3rd edition, New York, Harper & Row, 628 p.

Raymond, L.A., 2002, Petrology, the study of igneous, sedimentary & metamorphic rocks, 2nd edition: Boston, McGraw Hill, 720 p.

Shand, S.J., 1949, Eruptive rocks, New York, Wiley, 488 p.

Skinner, B.J. and Porter S.C., 2000, The dynamic Earth, an introduction to physical geology: New York, Wiley, 575 p plus appendices.