A Thermodynamic Study of the Catalina Schist Terrain

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8 May 2009

Abstract

The process of metamorphosis is of particular significance in geology because it leads to the production of many of the useable mineralogical resources that we extract from the earth. Understanding it properly is more difficult than the formation of igneous or sedimentary rocks because it involves so many factors (temperature, pressure, initial composition, time and others). The phenomenon of metamorphism is best understood in the context of thermodynamics, and as such this is how it will be laid out. One intriguing example of metamorphism in the Southern California region is the Catalina schist. This paper will lay out the basic principles of metamorphosis and use them to explain the Catalina schist terrain. In so doing, a basic understanding of both metamorphic thermodynamics and how they explain the Catalina schist should be attained.

The Catalina Schist is a formation of sedimentary, mafic, and ultramafic proliths which recrystallized under sub blueschist conditions. Radiometric dating shows that the amphibole formations in the schist formed approximately 110-115 million years old. After something on the order of 100 million years later, Sediment from the breakup of the Catalina Schist is present in many areas around the Los Angeles basin. (Bebout, Grove, Sorensen, & Platt, 1994). As a whole, the region is interesting because on the one hand many of the rocks seem to be of the variety formed under very high pressure but remarkably low temperature conditions, but the surrounding geology does not provide for such conditions. It is relevant to area of geologic research because it is unknown precisely how the particular metamorphic conditions came about that would be necessary to from the schist’s present.

A large portion of the Catalina schist is a blueschist material, which is formed under pressures normally characteristic of a depth of 15 to 30 kilometers, but at a temperature of only 200^{o}C to 400^{o}C. Under these conditions, some odd and blue minerals form, hence the name blueschist (Sadd). This is intriguing because as mentioned, the terrain of the Catalina schist does not seem to have the necessary conditions, normally seen in mountain building terrain. Further, there are minerals present in the terrain characteristic of high temperature formation (Bebout, Grove, Sorensen, & Platt, 1994). Blueschists in general are amphibole in composition.

Metamorphism is inherently linked to the field of thermodynamics. Phase diagrams show the regions of two independent variables in which different forms of the same chemical composition will exist. In metamorphism, the most important such diagram is the one representing phases with respect to temperature and pressure. To understand such a diagram, it is necessary to define Gibbs free energy (G) such that

$$G = E + PV - TS \qquad (1)$$

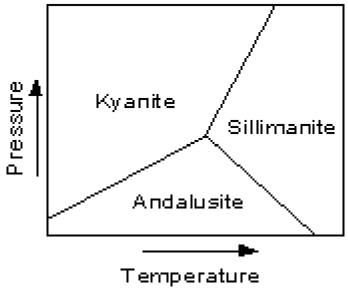
$$\text{And } E = Q - W \qquad (2)$$

$$\text{So } dE = dQ - PdV = TdS - PdV \qquad (3)$$

$$\text{and } dG = TdS - PdV + VdP + PdV - SdT - TdS \ (3)$$

$$\text{Or in equilibrium } dG = VdP - SdT \qquad (4)$$

E is just the energy, T is temperature in Kelvin, S is entropy (the measure of the disorder of a system), V is volume and P is pressure. For any system in equilibrium, the value for G should be minimized. Every reaction has a standard entropy and change in heat associated with it (called the standard entropies and heats of formation). This includes reactions involving the conversation of the same fundamental chemical contents from one type of mineral to another. By solving the above equation for any given standard reaction values (which will not be shown here) one can create equations which describe a line of pressure vs temperature at which dG=0. In this situation, both minerals are equally stable. This line separates the regions in which one mineral and another exist in equilibrium. For example



(Nelson, 2004)

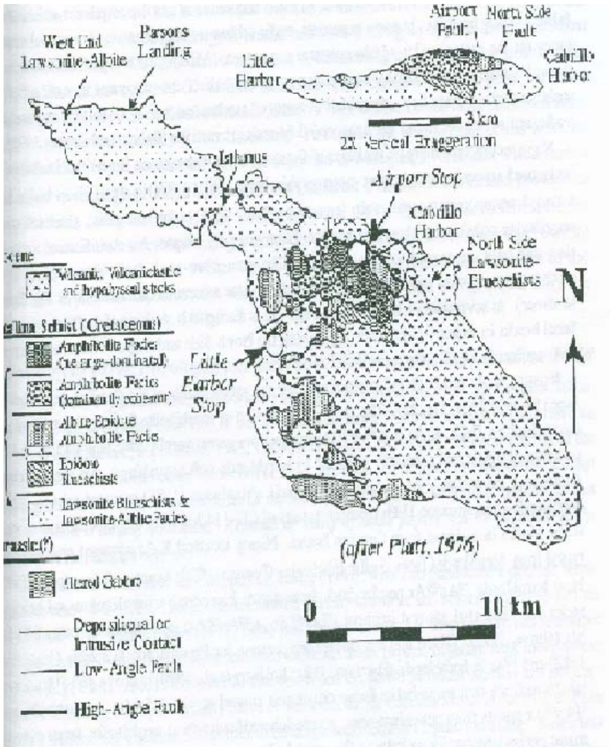
Metamorphism in general results from the movement of rocks from normal condition (300^oK and atmospheric pressure) so that the most energy favorable configuration for the system the metamorphic minerals that we see after the formation process. In reality, equilibrium does not come about instantly, because the solid state diffusion required for minerals within rocks to change is a very slow process (Nelson, 2004). This is what results in metamorphic grades: slate, schist, and gneiss. From the fact that blueschist is formed in the upper right region of the pressure temperature diagram for its component chemicals, we can conclude that the final products have a relatively low standard entropy of formation and a relatively strong response to volume as a result of pressure. Also note that the rate of solid state diffusion, which is what allows for the formation of metamorphic rocks by letting solids “flow” in some capacity is described (as are all chemical reaction’s rates) by the Arrhenius equation:

$$k=A*e^{(-E_a/R*T)} \quad (5)$$

The rate at which solids are able to diffuse through other solids, and thus the rate of metamorphism, increases exponentially with temperature. Therefore, below a certain temperature value it can be thought of as effectively being zero.

Now that we have a sufficient explanation for why different minerals form depending on the pressure and temperature history of the rock in which they develop. This environment history is referred to as the metamorphic facies. Normally, the geothermal gradient (increase in temperature with respect to depth) and how deep the material goes determine the type of metamorphic rock that forms (Nelson, 2003). The result problem however, is that blueschist materials require a geothermal gradient which is to shallow to exist under realistic scenarios. Thus, the added pressure of a tectonic plate collision is usually necessary (such as found in mountain building).

The Catalina schist itself consists of a number of units. The most significant ones are the amphibolite and ultramafic units and the blueschist unit. The amphibolites and ultramafic region consists of both high temperature history rocks and lower temperature amphibolites facies. However, it is dominated by the latter. Study of the lower regions here reveal high grade metamorphosis, and evidence of recrystallization but not partial melting and migmitization. This region is cut across mostly by shallow faults, and separated from other regions by somewhat steeper faults. The blueschist unit occupies a significant portion of the northern part of the island, and in interesting because among other things, it has a highly varying metamorphic grade. The Catalina schist as a whole consists of varying regions of mélange areas and coherent areas .As is only intuitive, the regions of coherence were likely formed at roughly the same time, and under largely uniform metamorphic conditions (pressure and temperature). (Bebout, Grove, Sorensen, & Platt, 1994).



(Bebout, Grove, Sorensen, & Platt, 1994)

The blueschist itself is the underlying material for most of the entire island, but is the surface material only in some areas. It was formed (as is the schist as a whole) from a mixture of sedimentary and mafic volcanic rocks. It is largely posited that the material that makes up the costal ranges was deposited on the ocean floor, and this formed the fundamental sediment that forms the island. The folding in the blueschist has little consistency, and occurs sporadically on both large and small scales. This may be the result of highly convoluted pressures being applied to sedimentary layers. “Rocks of the blueschist unit carry the minerals glaucophane, lawsonite, aragonite, and jaeditic pyroxene.” (Platt, 1976). The presence of these minerals, which is part of what characterizes the formation as a blueschist, are thought to have been stabilized late in their formation history by fluids coming in from ocean water. (Platt, 1976)

The amphibolite unit lies on top of the underlying blueschist in some areas of the Catalina region. The chemical composition of the amphibolite unit is not that fundamentally different from the other units, but its mineral content is quite different. It contains medium and coarse grains, in contrast to other regions which contain generally phyllitic grains. (Platt, 1976)

Something which makes the Catalina schist strange, and therefore an interesting area of research is the relevance of retrograde metamorphism. Retrograde metamorphism (the reverse metamorphosing of rocks upon returning to normal pressures and temperatures) generally does not occur. This is believed to be the case for a number of reasons, most notably that: chemical reactions take place at slower rates at lower temperatures, so upon cooling solid state diffusion and reverse reactions cannot take place (see above equation 5), fluids are required to drive the reaction one way or another and once driven off they do not return, and chemical reaction are catalyzed by the presence of fluids which are driven off during prograde metamorphism (Nelson, 2003). The structures of the Catalina schist show evidence of significant metamorphic activity at times past that of peak temperature and pressure. Rather than a reversing of the metamorphic grade as a whole the retrograde metamorphism manifests itself a veins of retrograde material which are underdeveloped by comparison to the surrounding material. In the amphibolite facies, a very large portion of the material was retrograded under greenschist like materials. Cooling histories for the formations can be investigated using radio metric Argon dating of white mica crystals. However, exactly why the retrograde metamorphism takes place is an ongoing area of research (Bebout, Grove, Sorensen, & Platt, 1994).

To finally bring all the data about the region together in the context of the groundwork in thermodynamics, tectonic mechanisms for the formation of the schist must be discussed. There are a few scenarios that have been suggested, 1: “The earliest development stages of subduction”, 2: “a ridge-trench encounter” 3: “post-subduction thermal reequilibration”, 4: “heightened sheer heating”. (Bebout, Grove, Sorensen, & Platt, 1994). In the first scenario, a high temperature gradient is established during the very early stages of subduction because the rocks are exposed to the full temperature of the lower crust without having any rocks in front of it heated first. In this manner, the schist could be accreted and pushed against itself without being exposed to higher temperatures that result in different facies, but the high temperature rocks found within the Catalina schist could still be exposed to the high temperatures below. In the second scenario, the overrunning of a trench by a subduction zone creates a short lived, very high temperature region, in which metamorphosis can occur in varying grades because the heat does not have time to diffuse properly. In the third scenario, isotherms within subduction zones equilibrate after subduction in a manner which accounts for the incongruity in temperature. In the fourth scenario, friction and heat from mechanical deformation cause localized heating while allowing the blueschist as a whole to form as expected.

The thermo-mineralogical mechanism for the formation of metamorphic rocks is one of the more complex things found in geological sciences. A proper understanding of the manner in which mineral which seem impossible, largely due to incongruity of formation temperatures, can help us better understand the underlying manner in which metamorphism continues to change out world. The thermodynamic anomalies of the Catalina schist are both intriguing and scientifically valuable.

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