JURASSIC PALEONTOLOGY AND SEDIMENTOLOGY IN SOUTHWESTERN UTAH

FACULTY

Mark A. Wilson, The College of Wooster, Director
H. Allen Curran, Smith College

STUDENTS

Kirsten M. Bannister, Whitman College
Emily K. Charette, George Washington University
Deborah L. Cussen, Carleton College
A. Mark Harper, The College of Wooster
Kelly Kilbourne, Smith College

VISITING SPONSORS

Patrick K. Spencer, Whitman College

Fe and increase an in Ca. SPMS garnets and hornblendes have similar Mg/(Mg+Fe) but higher Ca than their PMMMS counterparts (Figure 3). Distinct trends are apparent for calculated P-T condition for the SPMS and PMMMS (Figure 5). The PMMMS and SPMS yield similar pressures, whereas PMMMS samples yield a higher calculated temperature.

Discussion:

The most consistent explanation for the garnet zoning and GTB results is the reequilibration of SPMS and PMMMS garnet-amphibolites during the 1.7-1.8 Ga amphibolite event. Although the garnet zoning profiles for SPMS and PMMMS samples appear distinctly different they record the same event on garnets of different shape, size and composition. PMMMS garnets tend to possess flatter zoning profiles in Mg and Mn due to the increased effects of volume diffusion on zoning patternsof smaller garnets. Small SPMS garnets contain similar features (Figure 4).

Two factors cause SPMS and PMMMS garnets, which equilibrated under similar conditions, to yield consistently different temperatures. Graham and Powell's (1984) thermometer contains a correction for Ca content due to the non-ideal mixing of Ca. Ca has a much larger ionic radius than Mn and Fe and especially Mg. The presence of large amounts of Ca will limit the amount of smaller cations, especially Mg, incorporated into garnet's crystal structure. In high Ca garnets, Fe and Mn will be incorporated preferentially at the expense of Mg due to non-ideal mixing. The correction causes Ca rich samples (PMMMS) to yield higher temperatures than Ca poor samples (SPMS) given the same Mg/(Mg+Fe). BDM18A, from the SPMS, has a Ca content similar to PMMMS samples and yields a temperature similar to the trend of the PMMMS (Figure 5). Recent work (by Alcock, 1996) indicates that non-ideal mixing of Ca has decreasing effects on Mg/(Mg+Fe) with increasing metamorphic grade and volume diffusion, especially near the garnet core. Therefore, the Ca correction will tend to overestimate temperature (Alcock, 1996). The smaller, anhedral garnets of the PMMMS are much more effected by volume diffusion. Both of these factors lead to higher calculated temperatures in PMMMS samples. Simple calculations using Graham and Powell's calibration confirm that differences in Ca content and volume diffusion could lead to the variation seen in SPMS and PMMMS samples even if they equilibrated under similar conditions. There is no systematic variation in geographic location or metamorphic evolution which accounts for the variation in calculated temperature of SPMS and PMMMS samples. The pressure variation in both suites may be related to differential reequilibration during decompression on a clockwise P-T-T path.

The presence of relict garnet surrounded by symplectic OPX-plag in garnet-amphibolites from Thompson Ridge and aluminous lithologies (relict kyanite) throughout the range (Archuleta, 1994; Tierney, 1994; Monteleone, this volume) indicate that both the SPMS and ICMS/PMMMS were metamorphosed at higher P-T conditions than recorded in garnet-amphibolites. MMDS present in the ICMS/PMMMS yield GTB results similar to those in this study (Mohlman, 1996; Carmichal, this volume). However, it is possible that all evidence for earlier high P conditions in the MMDS could have been destroyed by retrograde metamorphism and hydration during the later amphibolite event. These factors are consistent with following chronology: 1) Metamorphism of the SPMS and PMMMS/ICMS at deep crustal levels during a high P, low T event; 2) Intrusion of MMDS; 3) Juxtaposition of the SPMS and ICMS/PMMMS; 4) High T, low P metamorphism recorded in garnet-amphibolites in the range.

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Jurassic Paleontology and Sedimentology in Southwestern Utah

Mark A. Wilson
Department of Geology, The College of Wooster, Wooster, OH 44691

H. Allen Curran
Department of Geology, Smith College, Northampton, MA 01063

INTRODUCTION

Southwestern Utah is a fascinating region for geological exploration and investigation. The scenery is some of the most spectacular in the country, especially in the geologically-rich National Parks of Zion and Bryce Canyon. The rocks are diverse, well exposed and easily accessible. Our 1997 Keck Geology Consortium project was based in St. George, Utah, concentrating on the fossils and sediments of the Carmel Formation (Middle Jurassic). We had two faculty and six students (later five), with one visiting advisor and one other visiting geologist. June 15-29 were spent in the field (staying in a dormitory at Dixie College in St. George), and June 30 - July 11 in the geological laboratories at The College of Wooster in Ohio. Figure 1 shows our field locations.

THE JURASSIC GEOLOGY OF SOUTHWESTERN UTAH

The Jurassic sedimentary rocks of southwestern Utah are products of a complex interplay of continental and shallow marine environments (Hintze, 1986, 1988). The Early Jurassic units are mostly non-marine sandstones, notably the Moenave and Kayenta Formations and the magnificent Navajo Sandstone. The Middle Jurassic rocks are of diverse marine and non-marine origins. The Carmel Formation is a sequence of shales, silts, sandstones and limestones recording a shallow interior seaway which extended north from the St. George area through central Utah into Wyoming. The sediments and fossils show that this sea was sometimes of normal salinity and at other times hypersaline and hemmed in by desert dune sands. There are no rocks from the Upper Jurassic in southwestern Utah -- the Carmel Formation is uncomformably topped by the Cretaceous Dakota Conglomerate, an extensive braided stream deposit.

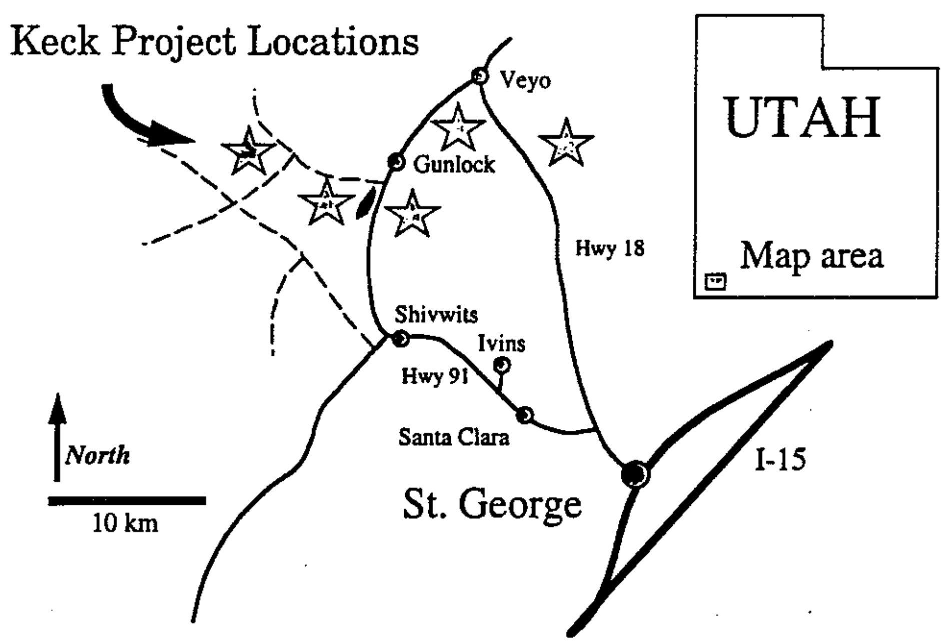

Figure 1. Location of the Keck-Utah 1997 summer field sites.

FIELDWORK

The Keck geology faculty members and students spent most field days in the vicinity of the Gunlock Reservoir, about 20 miles north of St. George. Where possible, students worked in pairs, with faculty members circulating among them with assistance and advice. The pioneering stratigraphic work by Nielson (1990) was especially helpful since we could field-check his stratigraphic columns as guides for our own. Some students concentrated on mostly paleontological topics, and others on sedimentological, but all made efforts to combine the two subdisciplines in their fieldwork.

LABORATORY AND LIBRARY WORK

The labwork was primarily preparing samples for later analysis. Several students made thin-sections using Wooster's Hilquist machine, and then examined them under petrographic microscopes. Others used a microscope equipped with cathodoluminescence to begin investigations of calcite grain and cement formation in the limestones. All students used the library heavily, starting with GeoRef computer database searches on their specific topics. Each student compiled a bibliography of relevant sources and wrote a report summarizing their work to date and what they intended to do back at their home campuses.

RECREATION

We spent one day exploring nearby Zion National Park, including a climb up Angel's Landing. That same day we visited Coral Pink Sand Dunes State Park. On another day we went on a historical tour visiting several pioneer sites, including the summer home of Brigham Young, the cabin of Jacob Hamblin, and the site of the Mountain Meadows Massacre. While in Wooster we went on a day trip to Caesar Creek Lake State Park in southern Ohio, where spectacular Upper Ordovician fossils were easily collected.

STUDENT PROJECTS

Kirsten Bannister (Whitman College) measured and described the lower three members of the Carmel Formation (Members A, B and C of Nielson, 1990) at three sites near Gunlock. She found 37 lithological units, including volcanic ashes, shales, siltstones and sandstones, and various limestones. Kirsten used a GPS receiver for precise location in the field, and standard field gear for description and sampling. Ripplemarks were frequent in these sections, so she used a Brunton compass to determine ancient current directions. Kirsten made dozens of thin-sections from her samples. She described in detail a series of shallowing-upward sequences among the paleoenvironments represented in the lower Carmel Formation.

Emma Charette (George Washington University) was most interested in the evolutionary dynamics of the invertebrate fauna in this restricted seaway. Starting with a provocative analysis of western U.S. Jurassic communities by Tang and Bottjer (1996), she is testing a model of community stability through changing environments known as "coordinated stasis". Tang and Bottjer (1996) received criticism that their assessment of the relevant fossil record was not done in sufficient paleontological detail (Schopf and Ivany, 1997), and that coordinated stasis analyses must include species-level data and account for morphological similarities and differences (Miller, 1997). Emma thus collected invertebrate fossils from two shell beds in the Carmel Formation in order to establish a morphological, taxonomic and paleoecological framework for future comparisons within the basin and without. Emma found the large bivalve *Plagiostoma* to be particularly abundant, along with a variety of smaller mollusks, echinoderms, corals and bryozoans. She has determined that these communities were dominated by epifaunal filter-feeders, many of which are found in Jurassic faunas around the world. The assemblages lack, however, ammonites and diagnostic foraminiferans, which makes it difficult to correlate them beyond "Middle Jurassic". Emma continued her work at George Washington University. She determined numerical abundances and taphonomic conditions, comparing her fossils with other faunas of the western Jurassic in the collections of the Natural History Museum at the Smithsonian Institution, especially to those collected by Ralph Imlay (1957, 1964).

Deborah Cussen examined oyster-rich balls (ostreoliths) found widely spread across two horizons near the top of the Carmel Formation at Gunlock Reservoir. The development of these ostreoliths has been recently hypothesized (Wilson et al., 1998), but that model was not stratigraphically tested. The ostreoliths are spherical accumulations of the oyster *Liostrea*, with minor numbers of the bivalve *Plicatula*, the bryozoan *Eurystrotos*, and the bivalve boring *Gastrochaenolites*. Wilson et al. (1998) suggested that the balls formed on the crests of submarine ooid dunes, and then were swept by storms into the lagoonal sediments where they are preserved. If so, they should show stratigraphic variations in size and shape along their horizons. Deb measured and sampled 178 ostreoliths from seven stratigraphic sections. She measured the three primary diameters of each and counted the number of right valves in place over the cemented left valves. She also sampled the matrix of the horizons at each site. In the lab, she placed her measurements into a computer database and drew Zingg diagrams of shapes for each site. She has documented significant statistical differences along the horizon consistent with the distribution-by-storms model.

Mark Harper (The College of Wooster) studied the cementation history of the hardgrounds in the Carmel Formation. Hardgrounds are synsedimentarily cemented seafloor sediments which formed rocky substrates. The most prominent Carmel hardground was described by Wilson and Palmer (1994), primarily in terms of paleoecology. Since then two additional hardgrounds were found in the Carmel, each significantly different from the first. The Jurassic was a time of "calcite seas", meaning that low-Mg calcite was the primary carbonate precipitate from seawater, rather than aragonite as is the condition today. Wilson et al. (1992) and Wilson and Palmer (1992) have postulated that hardgrounds formed very rapidly in calcite sea times, primarily because the calcite was formed in large part from contemporaneous dissolution of biogenic aragonite. Carbonate sediments rich in aragonite shell fragments could thus be "autocemented" in short intervals on the seafloors, forming hardgrounds. Mark tested this hypothesis by a petrological examination of the Carmel hardgrounds. One hardground is bioclast-rich and appears to fit the autocementation model, but the other two are micrite-rich and apparently formed from aragonite-poor sediments. Mark used petrographic and SEM techniques to reconstruct the cement history of these hardgrounds. He discovered that the earliest cement was a bladed low-magnesium calcite (LMC) which was not significant enough to actually firmly cement the hardground. That was done by a later blocky LMC cement. Mark showed by point-count analysis that the LMC cements could have been derived from dissolution of the aragonite bioclasts.

Kelly Kilbourne (Smith College) worked in Member D of the Carmel Formation, studying the numerous soft-sediment trace fossils. She used the trace fossils to distinguish paleoenvironments with a precision not available in the sedimentary record alone. She collected trace fossils from numerous locations in the Gunlock area, keeping careful stratigraphic notes on their distributions. In the lab she formally identified these traces, which she continued at Smith College. Kelly distinguished four trace fossil assemblages, all of which appear to be related to varying water energy regimes and substrate consistencies. Kelly found a surprising diversity of traces in the Carmel, few of which have been described from the North American Jurassic. Her work, combined with that of Smail and Wilson (1993), will be a significant addition to the paleontological literature of the Jurassic.

FIELD VISITORS

Kirsten Bannister's advisor, Pat Spencer of Whitman College, visited the project from June 23rd to the 26th. He was a great help to Kirsten as she measured and described her stratigraphic columns. Jordi de Gibert, a post-doctoral student at the University of Utah specializing in trace fossils, visited for several days. He made some interesting observations and gave us some good ideas about the distribution of particular ichnofossils.

OUTSIDE CONSULTANTS

Carol Tang, a new professor at Arizona State University who completed her doctoral dissertation on Jurassic fossils in the west, was a source of ideas and information. Various paleontologists at the Smithsonian, notably John Pojeta assisted us. Paul Taylor, a paleontologist at the Natural History Museum in London, identified several bryozoans collected on the project.

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