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Sequence stratigraphy of Lower Paleozoic rocks, Inyo Mountains, California

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SEQUENCE STRATIGRAPHY OF LOWER PALEOZOIC ROCKS, INYO
MOUNTAINS, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Robin M. Dornfest

May 2004

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ABSTRACT

Sequence Stratigraphy of Lower Paleozoic Rocks, Inyo Mountains, California

By Robin Dornfest

Uppermost Cambrian (?) through Lower Silurian strata in Mazourka Canyon and the Talc City Hills in the Inyo Mountains region of California can be grouped into five third-order sequences bounded by unconformities marked by basal conglomerates, facies mismatches, and the development of karst features.

The lowest sequence boundary separates the Upper Cambrian (?) Tamarack Canyon Dolomite from the overlying Ordovician Al Rose Formation. The second boundary is placed at the base of the Eureka Quartzite in the Talc City Hills and about 10 m below the top of the Badger Flat Limestone in Mazourka Canyon. The third boundary lies at the base of the Johnson Spring Formation in Mazourka Canyon and is 24 m above the base of the Eureka Quartzite the Talc City Hills, and the fourth boundary occurs just above the contact between the lower (Upper Ordovician) and middle (Lower Silurian) members of the Ely Springs Dolomite. Correlation of these sequence boundaries cratonward is somewhat problematic due to their outboard position on the paleoshelf.

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INTRODUCTION

This project involves the study of Upper Cambrian (?) to Lower Silurian rocks in the western Inyo Mountains in southeastern California located east of the Sierra Nevada, north of the Garlock fault, and west of Death Valley (Fig. 1). Marine sedimentary rocks in this region range in age from Late Precambrian to Middle Triassic. This section, which is 16,000 m thick, represents a miogeoclinal succession of what was thought to be almost continuous deposition of mixed carbonates and siliciclastics (Ross, 1966). With the exception of rocks in the Sierran roof pendants to the northwest recently correlated with those of the western Inyo Mountains (Stevens and Greene, 1999), and a few exposures in the Mojave Desert and the San Bernardino Mountains, the study area contains the westernmost occurrences of Paleozoic miogeoclinal formations in North America. In the Inyo Mountains region, these formations record a shelf to slope transition from shallow-water deposits to the east to those of deep water to the west (Stevens, 1991).

The purpose of this study is to interpret the sequence stratigraphic framework for mixed carbonate and siliciclastic deposits of Late Cambrian (?) through Early Silurian age in the western Inyo Mountains and Talc City Hills (Fig. 1). The study was accomplished by measurement and description of four sections, the development of a facies classification for interpretation of sedimentary depositional environments, and a sequence stratigraphic analysis.

Figure 1. Location map of field area. Red bars indicate location of measured sections; red dot indicates an additional area studied but not measured. Red box indicates area of map that is expanded.

Previous Work

The western Inyo Mountains have been extensively studied since the first reconnaissance of Mazourka Canyon by Edwin Kirk in 1912 (in Knopf, 1918), who stimulated interest in the area when he reported on several fossiliferous Paleozoic formations in the Independence quadrangle. Stauffer (1930) later measured sections and collected fossils near Kearsarge and Barrel Spring. In a systematic paleontological study of Ordovician faunas in this area, Phleger (1933) named and described two new Ordovician formations, the Mazourka and Barrel Spring formations. Ross (1963) elevated the Mazourka Formation to group status and named and described the Al Rose and Badger Flat formations. Hall and MacKevett (1955) described both the Paleozoic stratigraphy of the Darwin quadrangle and the structure of the Talc City Hills, and Pestana (1960) described and named several new species of coral from a unit in Mazourka Canyon he named the Johnson Spring Formation. Ross (1963) realized that the Upper Cambrian through Permian strata exposed in Mazourka Canyon marked the transition between the shallow-water eastern and the deeper-water western assemblage rocks. Ross (1965) mapped and described the geology of the Independence quadrangle, and later he (Ross, 1966) described in detail the Paleozoic formations of the area and correlated the lithostratigraphic units in the Inyo Mountain region with those farther east in Nevada. The nomenclature employed by Ross (1966) for the lower Paleozoic rocks of the eastern assemblage east of the area of this study (Fig. 2) has been accepted by all subsequent workers.

Figure 2. Correlation of formations from Mazourka Canyon to Death Valley (after Ross, 1966). Sections are generalized.

Based on conodont studies, Miller (1975) determined that the Ordovician-Silurian boundary exists within the Ely Springs Dolomite between the lower and middle members at Willow Springs Canyon in Mazourka Canyon.

Eberz (1985) discussed the environments of deposition of the Ordovician Badger Flat Limestone in Mazourka Canyon and the Talc City Hills and concluded that the Badger Flat Limestone is essentially a transgressive unit deposited on a broad carbonate ramp. Stevens (1986, 1991) described the shelf-to-basin transition of most of the Paleozoic rocks exposed in this area. Several other structural, stratigraphic, and sedimentologic studies have been completed for the area, none of which used a sequence stratigraphic approach. The maps of the Mazourka Canyon area (Ross, 1965) and of the Darwin quadrangle and adjacent areas (Stone et al., 1989) were used in this study as guides to the geology of the area of this study.

Field Work

Nine weeks of field work were completed during 1999 and 2000, in addition to numerous reconnaissance field trips in 1998. During this period, four stratigraphic sections were measured using a Jacob's staff or tape and compass. These sections include the uppermost Tamarack Canyon Dolomite where unfaulted, the Al Rose Formation, Badger Flat Limestone, Barrel Spring Formation, Johnson Spring Formation and its equivalent, the Eureka Quartzite in the Talc City Hills, and the Ely Springs Dolomite. Three sections, those at Willow Springs Canyon, Johnson Spring, and Badger Flat, are in Mazourka Canyon. The fourth is in the Talc City Hills adjacent to the White Swan Mine

(Fig. 1). Detailed descriptions of the lithology, sedimentary structures, fossils, and nature of the contacts of all the formations were recorded. During measurement, many of the lithologic units and contacts were traced up to 50 m along strike in order to evaluate continuity. Samples were collected and photographs were taken from each section in order to document lithologic changes that occur along strike.

In the field, carbonates were described using Dunham's (1962) classification scheme because it is based on depositional textures rather than types of grains contained within the rock, and thus is most appropriate for field identification. In this study, the term quartzite is used as an informal petrographic term to describe a sandstone consisting of more than 95 percent quartz that is tightly cemented with secondary silica. Such rocks are also referred to as quartz arenites (Folk, 1974). The facies names used in this paper are purely descriptive and are not to be confused with formal lithologic terms.

Local Geology

The southernmost stratigraphic section measured is located on the western flank of the Talc City Hills adjacent to the White Swan Mine (Fig. 1). The section is slightly overturned but is otherwise structurally uncomplicated. This complete section consists of the uppermost Tamarack Canyon Dolomite through the top of the Ely Springs Dolomite.

The southernmost section in Mazourka Canyon, located at Willow Springs Canyon (Fig. 1), consists of the upper part of the Tamarack Canyon Dolomite through the top of the Ely Springs Dolomite within the canyon and on the adjacent ridge to the north (here called Willow Springs Knob). This section dips 40 to 60 degrees to the

southwest. The section is partially metamorphosed, and the majority of the carbonates in the lower part of the section contain talc mineralization.

The Johnson Spring section is located approximately 5 km northwest of the Willow Springs Section (Fig. 1). This measured section consists of the upper part of the Al Rose Formation through the top of the Ely Springs Dolomite. The section is well preserved and extremely well exposed along a sharp ridge. The base of this section dips steeply (approximately 80 degrees) to the southwest, whereas the upper part of the section has a more moderate dip (40 degrees). The contact between the Al Rose Formation and the underlying Tamarack Canyon Dolomite is a strike fault that cuts out an unknown amount of both formations.

The Badger Flat section, located northwest of Johnson Spring, is the northernmost section studied (Fig. 1). This section consists of lower Badger Flat Limestone through the top of the Ely Springs Dolomite. This section dips 50 to 60 degrees to the southwest and is well preserved, although the lower Badger Flat Limestone is mostly covered due to subdued topography.

Local Stratigraphy and Regional Correlations

The Cambrian (?) Tamarack Canyon Dolomite, the lowest formation studied in the section, is easily recognized in both the Talc City Hills and Mazourka Canyon. According to Ross (1966) this unit in Mazourka Canyon averages 277 m thick and consists of about 194 m of medium-gray, laminated to thin-bedded dolomite, overlain by 83 m of medium-gray, massive dolomite. Only the upper part of the Tamarack Canyon

Dolomite is exposed in the Talc City Hills (Stone et al., 1989) where the contact with the overlying Al Rose Formation is placed at the base of the lowest occurrence of brown siltstone. At Willow Springs Canyon, the contact is placed at the base of a similar brown siltstone. To the east this unit probably correlates with the Nopah Formation (Ross, 1966; Fig. 2). In the Talc City Hills, the upper Tamarack Canyon Dolomite, previously thought to be latest Cambrian in age, has recently been shown to contain conodonts of Early Ordovician (Trempeleauan) age (John Cooper, personal communication, 2001).

Overlying the Tamarack Canyon Dolomite is the Lower Ordovician Al Rose Formation, which according to Ross (1966) averages about 122 m thick. In the Talc City Hills, this unit consists of a lower brown siltstone and mudstone with lesser limestone. In Mazourka Canyon and the Talc City Hills, the limestone in this formation tends to form irregular beds commonly appearing as “eyes.” Shale, mudstone, and lesser limestone form the upper part of this formation, which weathers to a distinctive reddish-brown color (Ross, 1966). In northern Mazourka Canyon, graptolites have been reported near the top of this formation (Ross, 1966). The Al Rose Formation is thought to be equivalent to the Goodwin Limestone to the east (Fig. 2), with the exception of the upper 15 m, which is thought to be equivalent to the Ninemile Formation (Ross, 1964).

Overlying the Al Rose Formation is the Middle Ordovician Badger Flat Limestone. This formation reportedly averages 150 m thick and is predominantly dolomite in the Talc City Hills (Stevens, 1991) and limestone in Mazourka Canyon (Ross, 1966). As measured by Ross (1966) in Mazourka Canyon at Johnson Spring, the lower 152 m consists of thin-bedded, highly-burrowed, bluish-gray carbonate with

abundant brown siltstone lenses. Black chert nodules are common near the base. The upper 28 m of the formation consists of irregular beds of medium-gray carbonate with a few brown, silty lenses (Ross, 1966). Fossils are abundant throughout the upper third of the formation and consist of gastropods, including *Maclurites* and *Palliseria*, and unidentified straight nautiloids (Ross, 1966). Oncolites (*Girvanella?*) are abundant in the same zone as the gastropods. In the Talc City Hills, the upper two-thirds of the formation are extensively brecciated (Eberz, 1985). The Badger Flat Limestone is thought to be equivalent to the Antelope Valley Limestone to the east (Ross, 1964).

According to Hall and MacKevett (1955), the Badger Flat Limestone in the Talc City Hills at the White Swan Mine is overlain by the Middle Ordovician Eureka Quartzite, which consists of three informal members. The lower and upper members are composed primarily of massive, pink to white, medium-grained quartzite, whereas the middle member is composed of impure, gray to brown, thin-bedded quartzite interbedded with massive quartzite. The Eureka Quartzite is recognized to the east of the Talc City Hills in the Death Valley region and throughout eastern Nevada (Ross, 1964).

In Mazourka Canyon, the Badger Flat Limestone is overlain by the Middle Ordovician Barrel Spring Formation (Ross, 1966). As measured by Ross (1966), this formation ranges from 20 m to 60 m thick. At Johnson Spring, Ross (1966) measured a lower impure quartzite and limestone 15 m thick, overlain by 9 m of medium-gray limestone interbedded with siltstone, and capped by 23 m of shale that weathers to a distinctive reddish brown. Brachiopods are common in the lower third of the formation.

The Middle Ordovician Johnson Spring Formation (equivalent to most of the Eureka Quartzite) averages 60 m thick and is only observed in Mazourka Canyon (Ross, 1966). According to Ross (1966), the basal unit at Johnson Spring consists of 11 m of white to yellow, crossbedded quartzite with carbonate cement. Overlying this is about 18 m of mixed quartzite and carbonate beds. This interval is overlain by about 10 m of massive white quartzite, followed by about 14 m of irregularly bedded, dark-gray limestone with a few silt-rich interbeds. Overlying this interval is a 6-m-thick, dark-gray, massive dolomite with minor black chert nodules, which is in turn overlain by 5 m of resistant, massive, white quartzite, which marks the top of the formation.

Ross (1964) correlated the Barrel Spring Formation and the overlying Johnson Spring Formation in the Inyo Mountains with the Eureka Quartzite to the east, which consists entirely of quartzite.

In the Talc City Hills, the Upper Ordovician/Lower Silurian Ely Springs Dolomite overlies the Eureka Quartzite, whereas in Mazourka Canyon it overlies the Johnson Spring Formation. The Ely Springs Dolomite averages 104 m in thickness in Mazourka Canyon (Ross, 1966) and consists of three informal members. At Johnson Spring, according to Ross (1966), the lower member is 43 m thick and consists of dark-gray dolomite with irregular and thin-bedded black chert interbeds in the lower half and scattered black chert nodules in the upper half; the approximately 24-m-thick middle member consists of gray to tan, well-bedded dolomite; and the upper member is about 37 m thick and consists of about 17 m of dark-gray, irregularly to thin-bedded dolomite with thin black chert interbeds and about 5 m of irregular layers of black chert with lesser gray

dolomite. This member is capped by 15 m of dark-gray, well-bedded to massive dolomite with scattered black chert nodules. Pelmatozoans are abundant in the lower and upper members. At Willow Springs Canyon, the Ordovician/Silurian boundary was placed at the contact between the lower and middle members by Miller (1975).

FACIES

A facies scheme was developed in order to better illustrate and understand lithologic patterns within the sections studied. Fourteen facies (Fig. 3) were recognized in the four measured sections (Plates 1, 2). These facies are based on gross lithology, color, sedimentary structures, bedding thickness, texture, amount of admixed or interbedded siliciclastic sediment, and fossils. These facies are directly related to specific depositional environments and provide much of the data used to interpret the sequence stratigraphy. Terminology used in the naming of these facies is a mix of both previously defined lithologic nomenclature and informal descriptive terminology.

Quartzite Facies

The Quartzite Facies is represented in all sections and is restricted to the Johnson Spring Formation and Eureka Quartzite, except for thin beds in the Barrel Spring Formation at Badger Flat, and in the Badger Flat Limestone in all sections with the exception of the Talc City Hills. This facies is easily recognizable and forms resistant cliffs and hogbacks in the field area. In the Talc City Hills, this facies appears sheet-like. In Mazourka Canyon, the nature of the deposit is considerably different. Channels filled with quartzite are incised up to 5 m into the underlying rocks, and thickness varies considerably along strike.

Figure 3. Interpreted positions of siliciclastic and carbonate facies relative to depth or distance from shore.

All quartzite beds, including units with different sedimentary structures, cements, and bedding types, are included in this facies. The quartz grains that make up the quartzite range from very fine to coarse sand and tend to be well rounded and extremely well sorted. Silica cement is present in the form of syntaxial overgrowths and is the dominant cement in much of the facies in the Talc City Hills and in southern Mazourka Canyon. Carbonate cement in the quartzites is common, but tends to be subordinate to silica cement. Calcite-cemented beds occur mainly in northern Mazourka Canyon. The color of weathered surfaces includes white, pink, gray, and light brown. A light-gray color tends to dominate fresh surfaces (Figs. 4, 5).

Sedimentary structures are rarely visible in the Quartzite Facies; however, rare low-angle cross stratification with sets 30 cm to 50 cm thick is present in the White Swan Mine and Johnson Spring sections. Outcrops range from massive to laminated, although the majority of the quartzites are massive. Laminated quartzites appear in the upper Badger Flat Limestone at Johnson Spring and thin-bedded quartzites are present near Badger Flat. No fossils have been recovered from this facies, but fossils have been recovered from other interbedded facies. Langenheim et al. (1956) reported corals, bryozoans, brachiopods, gastropods, sponges, pelecypods, and cephalopods from the interbeds in the Johnson Spring Formation in the Mazourka Canyon area.

One suggestion that the Quartzite Facies was deposited in a subtidal environment comes from what appear to be two, meter-scale offshore bars at the top of the Eureka Quartzite near Swansea. These two massive quartzite mounds are interbedded with

Figure 4. Quartzite Facies in the Johnson Spring Formation at Badger Flat. This outcrop is thin bedded and calcite cemented. Hammer is 35 cm long.

Figure 5. Quartzite Facies in the Johnson Spring Formation at Badger Flat. Lower unit is white, vitreous quartzite; middle unit is thin-bedded, carbonate-cemented quartzite; and upper unit is thin-bedded, brown quartzite. Hammer is 35 cm long.

dolomite typical of the overlying Ely Springs Dolomite. It is probable that the bars of the Eureka Quartzite are marine and formed in a tide-dominated environment, as suggested by Klein (1975) for deposition of the Johnson Spring quartzites in central Mazourka Canyon. Elsewhere, due to the general lack of sedimentary structures and fossils, it is difficult to determine the environment of deposition for the Quartzite Facies. For the purpose of this study, a range of shallow subtidal possibly to aeolian depositional environments is suggested.

Siltstone Facies

The Siltstone Facies occurs in the Barrel Spring Formation (Figs. 6, 7) and Johnson Spring Formation in all measured sections in Mazourka Canyon, and in the Al Rose Formation at Willow Springs Canyon. It also occurs in the Eureka Quartzite in the Talc City Hills. The predominant lithology of this facies is red- to brown-weathering siltstone, with a few interbeds of mudstone, shale, and quartzite. These rocks are gray to white on fresh surfaces. The siltstone is massive to laminated, contains rare sand-sized quartz grains, and is locally phyllitic. Ross (1966) reported small brachiopods within this facies in the Barrel Spring Formation at Johnson Spring in Mazourka Canyon. Based on the lack of sedimentary structures and the presence of whole fossils, this facies, where it is thick, is interpreted to have been deposited relatively near shore in the shallow subtidal zone, but below wave base.

Figure 6. Siltstone and Black Shale Facies in the Barrel Spring Formation at Willow Springs Canyon.

Figure 7. Siltstone Facies in the Barrel Spring Formation overlying the Black Shale Facies at Johnson Spring. Hammer is 35 cm long.

Carbonate-rich Clastic Facies

The Carbonate-rich Clastic Facies is predominant in the Al Rose Formation in the Talc City Hills (Figs. 8, 9) and at Willow Springs. It also has minor occurrences in the Badger Flat Limestone and Johnson Spring Formation at Badger Flat and the Middle Member of the Ely Springs Dolomite at Badger Flat. Rocks composing this facies include siltstone, mudstone, and shale with lesser micritic limestone. The clastic-rich beds in this facies tend to be light to dark brown, whereas the carbonates are predominantly light to dark gray. This facies generally weathers dark brown and orange. The bedding tends to be thin and irregular. These rocks contain small lenses or “eyes” of carbonate (Ross, 1966) called crepe structures by McAllister (1952). Soft-sediment deformation in the form of slump folds is common in this facies at both the Talc City Hills and Mazourka Canyon. No fossils were found within this facies. Based on the presence of the very fine-grained sediment and lack of evidence of currents, the depositional environment of this facies is considered to have been a subtidal shelf, below normal wave base.

Black Shale Facies

The Black Shale Facies, consisting of black shale and mudstone, occurs in the Barrel Spring Formation at Willow Springs and Johnson Spring (Figs. 6, 7). These rocks weather dark gray to black, tend to be thin bedded to laminated, and are locally phyllitic. No significant fossils were found in this facies although Ross (1966) reported occurrences of brachiopods, trilobites, bryozoans, and graptolites in Mazourka Canyon. Based on grain size, lithology, lack of sedimentary structures other than planar bedding, and the fossils reported by Ross (1966), the depositional environment is considered to

Figure 8. Carbonate-rich Clastic Facies near the top of the Al Rose Formation at the White Swan Mine. Rock hammer is 35 cm long.

Figure 9. Carbonate-rich Clastic Facies near the top of the Al Rose Formation at the White Swan Mine. Note subordinate amount of carbonate. Hammer head is 18 cm long.

have been relatively deep water, below storm-wave base. This facies is regarded as one of the deepest-water deposits identified in the area of this study.

Boundstone Facies

The Boundstone Facies (Figs. 10, 11) occurs sporadically in all formations with the exception of the Johnson Spring Formation and Eureka Quartzite. It is most prevalent in the Ely Springs Dolomite throughout Mazourka Canyon. The Boundstone Facies consists of cryptalgal laminations in either dolomite or limestone. Limestone in this facies ranges in color from light to dark gray; the dolomite is light to dark brown. Bedding generally is in the form of very fine parallel to wavy laminations. Locally admixed silt and fine quartz sand are observed in thin section.

Planar cryptalgal structures generally indicate deposition on a tidal flat. Desiccation features indicate that the stromatolites were subaerially exposed. The Boundstone Facies is interpreted as being peritidal, deposited on a broad tidal flat, most likely only covered with water during the high tides (Ross et al., 1989).

Massive Carbonate Facies

The Massive Carbonate Facies (Figs. 12, 13) occurs in the Tamarack Canyon Dolomite and Badger Flat Limestone at the White Swan Mine and Willow Springs, in the Johnson Spring Formation at Johnson Spring, and in the Ely Springs Dolomite in all sections. The dominant lithology in this facies is dolomite with minor occurrences

Figure 10. Boundstone Facies in the Ely Springs Dolomite at Badger Flat. Lens cap diameter is 5 cm.

Figure 11. Boundstone Facies in the Badger Flat Limestone at the White Swan Mine. Note desiccation structures. Lens cap diameter is 5 cm.

Figure 12. Massive Carbonate Facies in the Ely Springs Dolomite at the White Swan Mine. Hammer is 35 cm long.

Figure 13. Massive Carbonate Facies in the Tamarack Canyon Dolomite at the White Swan Mine. Hammer is 35 cm long.

of limestone in Mazourka Canyon. Colors range from bluish gray to light brown. Due to the recrystallization of the dolomite, the original lithology is impossible to determine, but the limestones appear to be mostly mudstones. No fossils have been observed within this facies. The Massive Carbonate Facies lacks sedimentary structures, most likely due to dolomitization; therefore, it is difficult to interpret the environment of deposition. Based on its close association with the Boundstone Facies and its common dolomitization, the Massive Carbonate Facies is considered lagoonal and may represent deposition in the intertidal zone and possibly the supratidal zone.

Oncolitic Facies

The Oncolitic Facies (Figs. 14, 15, 16, 17) occurs in all sections of the Badger Flat Limestone except for the Badger Flat section. This facies also occurs in the Johnson Spring Formation at Willow Springs, the Ely Springs Dolomite at Johnson Spring, Willow Springs Canyon, and the White Swan Mine, and the Tamarack Canyon Dolomite at the White Swan Mine.

The Oncolitic Facies consists of mudstone to packstone, with a few beds of grainstone and rare interbedded siltstone, and admixed fine quartz sand grains. Oncolites range in size from 0.5 cm to 4 cm and contain the algal form *Girvanella* (Ross, 1966). Intraclasts of mudstone and wackestone are common in this facies (Fig. 18). Light- to medium-gray colors tend to dominate the facies, although there are some bluish gray outcrops. Bedding ranges from thin to massive. Fossils are common in this facies. *Palliseria* and *Maclurites* as large as 8 cm in diameter (Fig. 19) are two gastropods

Figure 14. Oncolitic Facies in the Johnson Spring Formation at Willow Springs Canyon, located directly below the contact with the upper Quartzite. Oncolites are in a limestone matrix. Hammer head is 18 cm long.

Figure 15. Oncolitic Facies in the Ely Springs Dolomite at the White Swan Mine. Oncolites are in a dolomitic matrix. Section of hammer is 28 cm long.

Figure 16. Oncolitic Facies in the Ely Springs Dolomite at Willow Springs Canyon. Hammer is 35 cm long.

Figure 17. Oncolitic Facies at the base of the Ely Springs Dolomite in Willow Springs Canyon. Lens cap is 5 cm in diameter.

Figure 18. Oncolitic Facies containing oncolites and mudstone intraclasts in the Ely Springs Dolomite at Willow Springs Canyon. Hammer head is 35 cm long.

Figure 19. Oncolitic Facies containing *Palliseria* in the Badger Flat Limestone at the White Swan Mine. Pencil is 17 cm long.

commonly associated with the Oncolitic Facies in the Badger Flat Limestone. Oncolites tend to form in high-energy, shallow waters. Based on the presence of oncolites, admixed quartz sand, the close association with the Massive Carbonate Facies, and the presence of intraclasts, deposition of the Oncolitic Facies is considered to have occurred in very shallow-water shoals in the intertidal and shallow subtidal zones.

Mottled Carbonate Facies

The Mottled Carbonate Facies (Figs. 20, 21, 22, 23) occurs in all sections of the Badger Flat Limestone, in the Johnson Spring Formation at Willow Springs, and in the Al Rose Formation in the Talc City Hills. Petrographic analysis reveals that micritic limestone, wackestone, packstone, and grainstone all occur within the Mottled Carbonate Facies. Where dolomitic, the Mottled Carbonate Facies tends to weather orange to light brown in color. Where only limestone is present, bluish-gray to light-brown colors dominate. On fresh surfaces, both dolomite and limestone commonly are light to dark gray. The Mottled Carbonate Facies is thin bedded to massive. Siltstone is rare, although interbeds are observed locally. Straight cephalopods (Fig. 22) are present in the Johnson Spring and Badger Flat sections. Pelmatozoans are present in most sections, but they are a minor component of the rock. The mottling in the rock probably is due to disruption of bedding caused by burrowing organisms. This, coupled with the close association of this facies with the Oncolitic and Thin-bedded Limestone Facies, suggests that this facies was deposited in environments ranging from intertidal to subtidal.

Figure 20. Mottled Carbonate Facies in the Badger Flat Limestone at Badger Flat. Light-colored areas are mudstone and wackestone. Dark-colored areas consist of grainstone and packstone. Lens cap has a diameter of 5 cm.

Figure 21. Close-up of Mottled Carbonate Facies in the Badger Flat Limestone at Badger Flat. Lens cap has a diameter of 5 cm.

Figure 22. Mottled Carbonate Facies with a straight cephalopod in the Badger Flat Limestone at Badger Flat. Lens cap has a diameter of 5 cm.

Figure 23. Mottled Carbonate Facies in the Badger Flat Limestone at the White Swan Mine. Hammer is 35 cm long.

Hash Bed Facies

The Hash Bed Facies (Figs. 24, 25) occurs almost exclusively in the Badger Flat Limestone at Badger Flat, with minor occurrences in the Badger Flat Limestone at Willow Springs and in the Johnson Spring Formation at Willow Springs Canyon. The Hash Bed Facies consists of wackestone, packstone, grainstone, and fossil hash. These rocks weather to light to dark gray and bluish gray. Bedding ranges from thin to thick and tends to be irregular. Intraclasts composed of mudstone are common in this facies. Disarticulated pelmatozoans, trilobites, gastropods, and cephalopods are present in abundance in the Badger Flat Limestone at Badger Flat. Angular fossil fragments in this facies range in size from 1 mm to 7 cm and appear to be reworked. Based on the amount of energy required to rework the fossils and to introduce intraclasts, and the close association of this facies with the Oncolitic and Massive Carbonate Facies, this facies is interpreted as being intertidal to subtidal. It may represent deposition in tidal channels or subtidal environments during storm events.

Silty Carbonate Facies

The Silty Carbonate Facies (Figs. 26, 27) occurs in the Badger Flat Limestone in all sections, in the Tamarack Canyon Dolomite and Ely Springs Dolomite at the White Swan Mine, in the Ely Springs Dolomite at Willow Springs, in the Johnson Spring Formation at Willow Springs, and in the Al Rose Formation at Johnson Spring. Packstone and grainstone beds are interbedded with equal amounts of siltstone. Few sand-sized quartz grains were observed in the Willow Springs Canyon section. This

Figure 24. Hash Bed Facies in the Badger Flat Limestone at Johnson Spring with underlying Silty Carbonate Facies and overlying Thin-bedded Limestone Facies. Note intraclasts capping the Hash Bed Facies. Lens cap is 5 cm in diameter.

Figure 25. Hash Bed Facies in the Badger Flat Limestone at Badger Flat. Lens cap is 5 cm in diameter.

Figure 26. Silty Carbonate Facies in the Badger Flat Limestone at Willow Springs Canyon. Note that silty limestone in the middle part of the slab grades upward and downward into the Oncolitic Facies.

Figure 27. Silty Carbonate Facies in the Badger Flat Limestone at Willow Springs Knob. Hammer is 35 cm long.

facies tends to weather light to dark brown in outcrop, but it appears light to dark gray on fresh surfaces. The Silty Carbonate Facies commonly is thin bedded and locally contains low-angle cross-stratification and rare ripple marks on bedding planes. Minor pelmatozoan debris is present in the Silty Carbonate Facies in Mazourka Canyon. Based on the presence of packstone and grainstone, sedimentary structures including cross-stratification, and the close association with the Oncolitic Facies, the Silty Carbonate Facies is interpreted as a nearshore, subtidal to intertidal deposit.

Coral Limestone Facies

The Coral Limestone Facies crops out only in the Johnson Spring Formation at Johnson Spring. The original lithology is difficult to determine due to alteration, but in thin-section it appears to be a mudstone with black chert nodules and rugose corals (Pestana, 1960) that range in length from 3 to 7 cm. This facies weathers to a bluish-gray color, is thin bedded, and locally contains interbeds of reddish-brown siltstone. The Coral Limestone Facies appears to pinch out both north and south of the Johnson Spring section. Corals are the dominant fossil within this facies, although subordinate numbers of brachiopods, pelmatozoans, and gastropods are present. The close association of the Coral Limestone Facies with the Quartzite Facies at Johnson Spring suggests that it might represent deposition in a quiet lagoon behind an offshore bar.

Thin-bedded Limestone Facies

The Thin-bedded Limestone Facies (Figs. 28, 29) occurs in all sections of the Badger Flat Limestone. Minor occurrences of this facies are present in the Johnson

Figure 28. Thin-bedded Limestone Facies in the Badger Flat Limestone at Badger Flat. Lighter layers are mudstone and wackestone, whereas darker layers consist of packstone with lesser grainstone. Pen is 14 cm long.

Figure 29. Thin-bedded Limestone Facies with minor chert in the Badger Flat Limestone at Badger Flat. Lighter layers are mudstone and wackestone, whereas the darker layers are generally packstone with lesser grainstone. Lens cap is 5 cm in diameter.

Spring Formation at Willow Springs Canyon and Johnson Spring. The Thin-bedded Limestone Facies consists of interbedded carbonate mudstone, wackestone, packstone, and minor amounts of grainstone. Rare chert nodules, which appear to be of replacement origin, occur locally, and minor amounts of silt are admixed with these carbonates. These rocks are thin bedded to laminated, and layers are continuous over several meters. Weathered surfaces are light to dark gray, whereas fresh surfaces are most commonly light gray. Pelmatozoan fragments are present locally in this facies. The Thin-bedded Limestone Facies is very similar to the Mottled Carbonate Facies with respect to lithology, color, thickness of bedding, silt content, and the presence of pelmatozoans. These two facies are generally closely associated in the field, and differ primarily in the smaller degree of bioturbation in the Thin-bedded Limestone Facies.

Based on the textures of the rocks, the nature of the thin, regular beds, the close association with the Mottled Carbonate Facies, and fossils, this facies is thought to have been deposited subtidally and below normal wave base. Lack of burrows and reworking of the sediment in this facies points toward deposition in a low-energy, low-oxygen environment.

Cherty Carbonate Facies

The Cherty Carbonate Facies (Figs. 30, 31) occurs in the Badger Flat Limestone and the Ely Springs Dolomite in all sections. It is also observed in the Al Rose Formation and the Johnson Spring Formation at Willow Springs Canyon and at Johnson Spring.

Figure 30. Cherty Carbonate Facies in the Ely Springs Dolomite at Willow Springs Canyon. Hammer is 35 cm long.

Figure 31. Cherty Carbonate Facies in the Ely Springs Dolomite at the White Swan Mine. Hammer is 35 cm long.

Carbonate mudstone, wackestone, packstone, and grainstone are represented in this facies. These beds may be composed of either limestone or dolomite. The chert, which occurs in both nodular and bedded forms, is thought to be secondary with sponge spicules as the most likely source of silica (Ross, 1966). The chert commonly defines the bedding in this thin- to thick-bedded facies. The carbonates, which range from light to dark gray on weathered surfaces, are dark gray on fresh surfaces. The chert is black on fresh surfaces, but it weathers to light gray. This facies contains very few fossils, although pelmatozoans, sponge spicules, and radiolaria have been reported by Ross (1966). Based on the abundance of chert and its relation to sponge spicules, lack of sedimentary structures other than bedding, and the presence of radiolaria, this facies is considered a relatively deep, subtidal deposit.

Black Chert Facies

The Black Chert Facies (Figs. 32, 33) occurs in the Upper Member of the Ely Springs Dolomite in all sections and in the Middle Member at Badger Flat. The chert is black to dark gray on weathered surfaces and black on fresh surfaces. The chert is commonly massive or irregularly bedded, but locally it may be laminated to thin bedded. Highly chaotic slump folds are present northwest of Johnson Spring in the Ely Springs Dolomite. No fossils were recovered from this facies, although Ross (1966) reported possible radiolaria. Based on the lithology and the fact that it is overlain by the relatively deep-water Vaughn Gulch Limestone or Sunday Canyon Formation, both of which contain sediment gravity-flow deposits (Ross, 1966), the Black Chert Facies is considered a relatively deep, subtidal, offshore deposit, deposited well below storm wave base.

Figure 32. Black Chert Facies in the upper member of the Ely Springs Dolomite overlying the Massive Carbonate Facies at Badger Flat. Black Chert Facies here is highly brecciated.

Figure 33. Black Chert Facies in the Ely Springs Dolomite at Badger Flat. Thin-bedded limestone of the Sunday Canyon Formation directly overlies the chert in this figure. Lens cap diameter 5 cm.

SEQUENCE STRATIGRAPHY

Terms and Concepts

A sequence as defined by Mitchum (1977) is a succession of genetically related strata bounded by unconformities and their correlative conformities. Thus, sequence stratigraphy allows time correlations and tracks facies migration over time. This integrated approach is used in this study to divide stratigraphic columns into units based on chronostratigraphic bounding surfaces. Bounding surfaces within the measured sections are not only based on unconformities, but also facies mismatching and parasequence set patterns. Previously, lithostratigraphic correlations of formations have been successful (Ross, 1966). However, this does not allow one to interpret basin development based on time-equivalent units because formational boundaries are based on lithostratigraphy. Lithostratigraphic correlations have been shown to be useful in regional lithologic comparisons and for mapping purposes. These lithologic units may not be the same as chronostratigraphic units; in fact, most formations are time transgressive, whereas unconformities and their correlative conformities are always equivalent in age.

In order to apply sequence stratigraphic principles it is first necessary to define the terms and concepts used therein (Fig. 34). Here the terms and concepts are taken directly from, or modified after, Van Wagoner et al. (1988) unless otherwise stated.

Figure 34. Sequence stratigraphic framework based on Van Wagoner et al. (1988). TST = Transgressive systems tract; HST = Highstand systems tract; LST = Lowstand systems tract.

The surfaces of erosion or non-deposition that separate sequences are of two main types. A Type-1 sequence boundary (Posamentier et al., 1988) forms when sea level drops below the shelf-slope break, in most cases resulting in an unconformity that is accompanied by an abrupt shift in shoreline facies toward the basin. This facies shift is most commonly referred to as a forced regression. The basinward migration of facies will tend to manifest itself in an abrupt change from deeper-water facies to those of a shallower-water environment. Down dip the unconformity becomes conformable, with an abrupt facies change as the only evidence of sea-level drop. These facies mismatches become increasingly difficult to recognize with increasing water depth. The unconformity itself commonly is associated with widespread subaerial exposure and can display tens to hundreds of meters of relief. In the case of siliciclastic settings, incised valleys are common and tend to show the greatest relief. In the carbonate realm, dissolution and karstification are common, with the width of the affected areas ranging from meters to kilometers (Handford and Loucks, 1993).

According to Posamentier and James (1993), a Type-2 sequence boundary occurs because of a deceleration followed by acceleration in relative sea level rise. No relative sea level change occurs, as the maximum rate of eustatic fall is less than the rate of subsidence. In the case of a Type-2 sequence boundary, the marine deposits from the previous highstand can be subaerially exposed but are not eroded. This type of sequence boundary is almost impossible to determine in outcrop (Van Wagoner et al., 1990). As no Type-2 sequence boundaries have been recognized in the field area, they will not be considered any further.

Parasequences and parasequence sets are the building blocks of sequences. It is therefore very important to understand their stacking patterns in order to interpret different aspects of the sequence in which they are contained. Parasequences are genetically related strata bounded by marine flooding surfaces or their correlative surfaces (Van Wagoner et al., 1990). Genetically related strata form in lateral continuity, and therefore in the vertical perspective hold true to Walther's Law. A parasequence represents a single flooding event followed by basinward progradation.

Scale tends to be unimportant in parasequences. Individual parasequences can range from less than a meter to tens of meters in thickness and can have a temporal range of tens to hundreds of thousands of years (Van Wagoner et al., 1990). Not all meter-scale successions of strata are parasequences, but some successions of hundreds of meters of strata are.

Parasequences can be grouped into parasequence sets, which consist of several parasequences that form one of three overall patterns (Van Wagoner et al., 1990). These are described as progradational (forestepping), aggradational, or retrogradational (backstepping) parasequence sets.

A progradational parasequence set consists of a succession of parasequences, each one building out farther basinward than the underlying parasequence (Fig. 35). In outcrop, the progradational parasequence set is recognized by the progressive appearance of increasingly shallow-water facies higher in the set. This also results in the loss of deeper water facies higher in the same set. Progradational stacking is the result of long-term creation of accommodation space being outpaced by sedimentation. The shallowing

Figure 35. Illustration of a progradational parasequence set consisting of several parasequences, based on Van Wagoner et al. (1990). Red rectangle outlines the vertical succession of parasequences that represents the progradational parasequence set.

gained in one parasequence is greater than the deepening produced above the underlying flooding surface. Progradational parasequence sets will have a net basinward migration of facies.

Aggradational parasequence sets contain parasequences that all tend to prograde to approximately the same point (Fig. 36). The general stacking pattern in the parasequence set displays no net shallowing or deepening, merely a stable succession of repeated parasequences. The result of aggradation is the lack of migration of facies either landward or basinward. In carbonates, aggradation is commonly short lived and the pattern becomes progradational because carbonate production rates generally outpace subsidence rates (Montanez and Osleger, 1996). If development of accommodation space is balanced with sedimentation for an extended period, an aggradational parasequence set could become very thick (Montanez and Osleger, 1996).

Retrogradational parasequence sets are transgressive and each successive parasequence progrades less basinward than the one underlying it (Fig. 37). The net pattern is that of deepening upward. In clastic systems, a fining- and thinning-upward pattern is also generally associated with retrogradation; in carbonate settings, an upward thickening in parasequences tends to dominate (Montanez and Osleger, 1996). Parasequence sets displaying retrogradational stacking are the result of accommodation space being created at a rate faster than that of sedimentation.

Type-1 sequences are divided into three systems tracts: lowstand, transgressive and highstand, as shown in Figure 34. A systems tract is a three-dimensional assemblage

Figure 36. Illustration of an parasequence set consisting of several parasequences. Based on Van Wagoner et al. (1990). Red rectangle outlines the vertical succession of parasequences that represents the aggradational parasequence set.

Figure 37. Illustration of a retrogradational parasequence set consisting of several parasequences. Based on Van Wagoner et al. (1990). Red rectangle outlines the vertical succession of parasequences that represents the retrogradational parasequence set.

of lithofacies, which form as coeval depositional systems (Posamentier et al., 1988).

Systems tracts are defined by their position in the sequence and the stacking pattern of parasequence sets within them. The lowstand systems tract lies directly above a Type-1 sequence boundary. Contained within this systems tract is a set of depositional systems related to a relatively low stand of sea level. Accommodation space forms at a slower rate than sedimentation, resulting in progradational parasequence sets.

Directly overlying the lowstand systems tract is the transgressive surface (Fig. 34) marked by a flooding surface. This surface marks the transition from falling or relatively static sea level to a rise in sea level. Updip, the transgressive surface may merge with the underlying sequence boundary. Overlying the transgressive surface is the transgressive systems tract. Contained within this systems tract is a retrogradational parasequence set.

The maximum flooding surface (Fig. 34) lies above the transgressive systems tract. This surface marks the transition from retrogradational to aggradational stacking. There is a rough correlation between the maximum flooding surface and the highest rate of sea level rise (Van Wagoner et al., 1990). Here, the center of the deepest water facies in the sequence is considered to represent the maximum flooding surface.

Overlying the maximum flooding surface is the highstand systems tract. Aggradational stacking patterns dominate the lower part of the highstand systems tract, but progradational patterns will commonly develop in the upper part of this systems tract. During the development of the highstand systems tract the creation of accommodation space is outpaced by sedimentation and facies migrate basinward. The highstand systems

tract is directly overlain by either a Type-1 or a Type-2 sequence boundary (Van Wagoner et al., 1990).

Outline of the Sequences

Four type-1 sequence boundaries are recognized in the Upper Cambrian (?) to Lower Silurian section throughout the study area. These four surfaces bound three complete sequences. Two partial sequences also are recognized, but the full extent of these sequences is not discussed in this study. From lower to upper positions these sequences are numbered 1-5, respectively. This is presented in Figure 38 and Plates 1 and 2.

Due to the scope of this study, only the upper part of Sequence 1, a highstand systems tract, was studied. This part of the sequence, represented by the upper part of the Tamarack Canyon Dolomite, was observed in the Talc City Hills and at Willow Springs Canyon in Mazourka Canyon. Sequence Boundary 1 separates the highstand systems tract of Sequence 1 from the overlying Al Rose Formation, which marks the base of Sequence 2. Sequence Boundary 1 is marked by a well developed unconformity that is observed in both the Talc City Hills and Willow Springs Canyon.

Sequence 2 consists of a transgressive systems tract with an overlying highstand systems tract, both of which are observed in the Talc City Hills and Mazourka Canyon. This sequence includes all of the Badger Flat Limestone in the Talc City Hills and all but the uppermost part of the Badger Flat Limestone in Mazourka Canyon. Sequence Boundary 2 directly overlies the highstand systems tract of Sequence 2.

Figure 38. Generalized correlation of sequences from all measured sections in the study area. S = Sequence, SB = Sequence Boundary, MFS = Maximum Flooding Surface, TS = Transgressive Surface, HST = Highstand Systems Tract, TST = Transgressive Systems Tract, LST = Lowstand Systems Tract. Systems tracts are color coded, Blue = HST, Green = TST, Yellow = LST. Figure is diagrammatic; see Plates 1 and 2 for scaled drawings.

Directly overlying Sequence Boundary 2 are the lowstand, transgressive, and highstand systems tracts of Sequence 3. This complete sequence is observed throughout the Talc City Hills and Mazourka Canyon and includes the upper Badger Flat Limestone and the Barrel Spring Formation in Mazourka Canyon and the lower Eureka Quartzite in the Talc City Hills. The sharp contact between the relatively deep-water Siltstone and Black Shale Facies of the Barrel Spring Formation and the shallow-water Quartzite Facies of the Johnson Spring Formation, marked by channels cut into the underlying siltstones, indicates the position of Sequence Boundary 3 in Mazourka Canyon.

Sequence 4 directly overlies Sequence Boundary 3. Lowstand, transgressive, and highstand systems tracts are observed in the Talc City Hills. In Mazourka Canyon all three systems tracts are present at all sections with the exception of Badger Flat. At this locale, only the lowstand and transgressive systems tracts are present.

Sequence Boundary 4 is a well-developed unconformity less than 10 m above the contact between the lower and middle members of the Ely Springs Dolomite. This surface is observed in both the Talc City Hills and Mazourka Canyon. At all locations, with the exception of Badger Flat, a thin bed of breccia directly underlies this exposure surface. At Badger Flat, this unconformity cuts farther down into the section, so that the breccia in the Ely Springs Dolomite is in contact with the Johnson Spring Formation. The lower member of the Ely Springs Dolomite and probably part of the upper Johnson Spring Formation apparently were eroded away during the development of Sequence Boundary 4.

Sequence 5, represented by the middle and upper members of the Ely Springs Dolomite, directly overlies Sequence Boundary 4. Due to the scope of this study, only the lower part of Sequence 5 was investigated. At Badger Flat, breccias that overlie Sequence Boundary 4 are interpreted to represent a lowstand wedge that pinches out to the southeast. The remainder of the upper part of the Ely Springs Dolomite in Mazourka Canyon is considered to represent a transgressive systems tract.

Sequence 1

Massive dolomite of the Cambrian (?) Tamarack Canyon Dolomite in the Talc City Hills and Mazourka Canyon comprises the upper part of Sequence 1. Due to the scope of this study, faulting in some sections, and the lack of exposure in others, only the uppermost deposits of Sequence 1 were studied for this project.

At the White Swan Mine, only the upper 13.5 m of the Tamarack Canyon Dolomite was measured. Massive gray dolomite of the Massive Carbonate Facies that makes up the basal 6.5 m of the measured section (Plate 1) is highly recrystallized. This unit is overlain by 3 m of gray, oncolitic dolomite of the Oncolitic Facies, 2.5 m of Silty Carbonate Facies, 1 m of dolomitic Boundstone Facies, and 0.5 m more of Oncolitic Facies (too thin to show on Plate 1). These facies all represent deposition in very shallow water (Fig. 3). Sequence Boundary 1, which is equivalent to Transgressive Surface 1, occurs directly above these deposits and separates Sequence 1 from the overlying Sequence 2 (Figs. 38 and 39).

Figure 39. Sequence Boundary 1 (SB-1) at the White Swan Mine in the Talc City Hills. TST = Transgressive systems tract; HST = Highstand systems tract. Hammer is 35 cm long.

At Willow Springs Canyon the upper 10 m of the Tamarack Canyon Dolomite was measured. At this location, this unit consists of mottled gray dolomite of the intertidal Massive Carbonate Facies. Sequence Boundary 1 and Transgressive Surface 1 are placed at the top of the Tamarack Canyon Dolomite as mapped by Ross (1966). At Johnson Spring and Badger Flat, this upper part of Sequence 1 was not observed due to faulting and covered section.

Sequence Boundary 1 is marked by a well-developed disconformity that separates the highstand deposits of Sequence 1 from the transgressive systems tract of Sequence 2. At the White Swan Mine, Sequence Boundary 1 and Transgressive Surface 1 are placed at the top of the Tamarack Canyon Dolomite as mapped by Stone et al. (1989), below the lowest occurrence of Carbonate-rich Clastic Facies, represented by the basal beds of the Al Rose Formation (Fig. 38). Sequence Boundary 1 is somewhat irregular and displays up to 0.5 m of relief in the Talc City Hills. At Willow Springs Canyon, Sequence Boundary 1 separates the Tamarack Canyon Dolomite from the Al Rose Formation of Ross (1966). At this location, Sequence Boundary 1 is placed above an incision into underlying strata up to 0.5 m, similar to that observed in the White Swan Mine section.

Sequence 2

In the Talc City Hills and Mazourka Canyon, the Al Rose Formation and the majority of the Badger Flat Limestone compose Sequence 2 (Fig. 38). This sequence is thickest at the White Swan Mine (201 m), generally thinning northwestward (Plate 1). At Willow Springs Canyon, the sequence is 115 m thick. At Johnson Spring and Badger

Flat, where the section appears to be incomplete due to faulting, thicknesses of 141.5 m and 116.5 m, respectively, were measured. Systems tracts contained within Sequence 2 are well developed. They consist of a transgressive systems tract and an aggradational to progradational highstand systems tract that thins irregularly to the northwest. No basal lowstand systems tract is recognized within the study area (Fig. 38).

The transgressive systems tract is best developed in the Talc City Hills at the White Swan Mine. The onset of transgression is noted at the base of the Al Rose Formation. This interpretation is based on the presence of a basal 0.5-m-thick bed consisting of oncolites up to 3 cm in diameter intermixed with reworked clasts of Tamarack Canyon Dolomite up to 10 cm in length that form a flat-pebble conglomerate. This bed is overlain by beds displaying a decrease in carbonate, increase in silt content, and noticeable thinning in bedding up section. This stacking pattern is interpreted to represent a deepening event. This transgressive systems tract is 40 m thick and includes the Al Rose Formation and the lower half of the 0.5-m-thick Cherty Carbonate Facies that marks the base of the Badger Flat Limestone as mapped by Stone et al. (1989). Maximum Flooding Surface 1 is placed within the Cherty Carbonate Facies, which is interpreted to represent the deepest water deposit in the transgressive systems tract (Fig. 38).

At Willow Springs Canyon the transgressive systems tract is 44.2 m thick (Plate 1) and includes the entire Al Rose Formation (38.7 m) and 5.5 m of the 11-m-thick basal cherty limestone of the Badger Flat Limestone as mapped by Ross (1966). The Al Rose Formation at this location consists of a basal Silty Carbonate Facies (2.2 m) overlain by

9.5 m of Siltstone Facies. Overlying this bed is a 12-m-thick interval of Carbonate-rich Clastic Facies overlain by 5.5 m of siltstone with rare limestone beds less than 0.5 m thick. The transgressive systems tract is capped by 15 m of Boundstone Facies and the lower one-half of the thick-bedded Cherty Carbonate Facies, the base of which marks the base of the mapped Badger Flat Limestone (Ross, 1966).

At Johnson Spring, only the upper part of the Al Rose Formation was observed due to faulting. The incomplete transgressive systems tract is 18.5 m thick. The lower 12.5 m of this deposit is represented by Silty Carbonate Facies of the Al Rose Formation. Overlying this interval is 6 m of interbedded Cherty Carbonate and Massive Carbonate Facies, which marks the base of the mapped Badger Flat Limestone (Ross, 1966). At Badger Flat, the Al Rose Formation and 3.5 m of the thick-bedded Cherty Carbonate Facies at the base of the Badger Flat Limestone are included in the transgressive systems tract. At this location the Al Rose Formation, which is composed of typical Silty Carbonate Facies, is too poorly exposed for measurement.

Thus, throughout the study area an overall deepening event can be recognized within the Al Rose Formation up into the basal chert-rich zone in the Badger Flat Limestone. This deepening event is shown by a retrogradational stacking pattern of facies from the Silty Carbonate Facies to the relatively deeper-water Cherty Carbonate Facies (Plate 1). Little is known about the geometry of the transgressive systems tract, as the only complete sections measured are located in the Talc City Hills at the White Swan Mine and at Willow Springs Canyon.

Overlying the transgressive systems tract above Maximum Flooding Surface 1, which is placed within the middle of the cherty limestone beds that occur at the base of the Badger Flat Limestone (Fig. 38), are the highstand deposits of Sequence 2. The highstand systems tract is well developed throughout the study area. Both aggradational and progradational stacking of facies are observed at all locations. Aggradation is represented by a thick package of Thin-bedded Limestone Facies or Mottled Carbonate Facies, which is present in the White Swan Mine and Johnson Spring sections (Plate 1). Progradation is represented in two of four sections higher in the upper Badger Flat Limestone by a shallowing-upward from the Thin-bedded Limestone and Mottled Carbonate Facies and the Oncolitic Facies into shallower water Boundstone Facies (Plate 1).

At the White Swan Mine, the highstand deposits are contained entirely within the Badger Flat Limestone. A 41.5-m-thick succession of thin-bedded limestones, mottled limestone, and massive limestone is interpreted to represent an aggradational stacking of facies (Plate 1). These beds are overlain by 65.5 m of dolomite consisting of interbedded Oncolitic and Mottled Carbonate Facies, suggesting a major progradational event. This progradational succession coupled with the underlying aggradational stacking pattern fits well with documented highstand systems tracts (Handford and Loucks, 1993). Overlying these beds is 56 m of intermixed mottled dolomite, silty dolomite, and dolomitic boundstone. Contained within the lower half of the upper 22.5 m of these interbedded carbonates are large pods of quartzite (Plate 1 and Fig. 38). These pods will be discussed in the following paragraphs related to Sequence Boundary 2. These overall shallowing

and thickening upward deposits (Plate 1) are interpreted to represent continued progradation of shallow-water facies basinward.

Throughout Mazourka Canyon the highstand systems tract is contained entirely within the Badger Flat Limestone (Fig. 38) as mapped by Ross (1966). At Willow Springs Canyon, the 66-m-thick section above the Cherty Carbonate Facies (10 m thick) is placed within the highstand systems tract, of which the lower 12 m is interpreted to represent aggradation. This package indicates no overall migration of facies either basinward or shoreward. Contained within this aggradational package are mostly the Silty Carbonate and Oncolitic Facies (Plate 1). Overlying the aggradational package is 54 m of mostly mixed Oncolitic Facies and Silty Carbonate Facies representing progradation.

At Johnson Spring, 122 m of section are recognized as highstand deposits, which display both aggradational and progradational stacking patterns (Plate 1). Overlying the Cherty Carbonate Facies, which contains the maximum flooding surface, is 11 m of Silty Carbonate Facies, overlain by 80.5 m of interbedded Thin-bedded and Mottled Carbonate Facies (Plate 1). These deposits are interpreted as aggradational in nature because the inferred water depth is roughly constant.

Overlying the aggradational phase of the highstand systems tract are 23 m of section containing interbedded Oncolitic Facies, Mottled Carbonate Facies, Thin-bedded Carbonate Facies, Silty Carbonate Facies, and Boundstone Facies containing planar stromatolites. Based on the apparent shallowing-upward, this interval is interpreted as progradational.

At Badger Flat, 113 m of section within the Badger Flat Limestone, consisting primarily of the Mottled Carbonate Facies interbedded with lesser amounts of the Hash Bed Facies (Plate 1), are recognized as representing a highstand deposit. With the exception of a thin quartzite bed, these deposits display no indication of facies migration, and are considered aggradational. The quartzite bed observed 27 m below the contact with the overlying Barrel Springs Formation is most likely a minor progradational feature.

Sequence Boundary 2 is a well-developed disconformity that defines the top of Sequence 2. This bounding surface separates the highstand deposits of Sequence 2 from the overlying lowstand systems tract of Sequence 3. Sequence Boundary 2 is best observed at the White Swan Mine (Fig. 40). This surface is placed at the contact between the Badger Flat Limestone and Eureka Quartzite as mapped by Stone et al. (1989). It is expressed as a disconformity with little relief. In addition, clasts of dolomite occur in the basal bed of the Eureka Quartzite above the unconformity. Underlying the Eureka Quartzite and within the underlying the Badger Flat Limestone are sand-filled cavities and grikes (Figs. 41, 42). These dissolution features are not observed directly connected to the base of the Eureka Quartzite, but these quartz grains are very similar in size and roundness to those in the basal Eureka Quartzite. The sand-filled cavities and grikes are therefore inferred to connect with the Eureka Quartzite out of view. The majority of these features occur as elongate tabular bodies oriented roughly perpendicular to bedding in the Badger Flat Limestone (Fig. 42). One large (~6 m diameter) sand-filled cavity (Fig. 41) was observed to the southeast of the measured section. Similar sand-filled features have

Figure 40. Sequence Boundary 2 (SB-2) at the White Swan Mine. Note light-colored Badger Flat Limestone lithoclasts (arrow) in the basal Eureka Quartzite. Lens cap is 5 cm in diameter.

Figure 41. Quartzite-filled cavity in the Badger Flat Limestone in the Talc City Hills.

Figure 42. Quartzite-filled grikes in the Badger Flat Limestone in the Talc City Hills. Blue pencil in center of photograph is 15 cm long.

been described by Cooper and Keller (2001) in the Nopah Range and other locations to the east.

At Willow Springs Canyon, Sequence Boundary 2 is placed within the Badger Flat Limestone, 29.5 m below the contact with the Barrel Spring Formation. This surface is placed at the base of massive quartzite that contains abundant talc mineralization. At Johnson Spring, Sequence Boundary 2 is placed within the Badger Flat Limestone at the base of a quartzite bed 8.8 m below the contact with the overlying Barrel Spring Formation (Fig. 43). At Badger Flat, Sequence Boundary 2 is placed within the Badger Flat Limestone at the base of a massive quartzite bed 11.5 m below the contact with the Barrel Spring Formation (Plate 1). Placement of Sequence Boundary 2 in all three sections at this particular stratigraphic interval is based on the presence of quartzite within the Badger Flat Limestone, incision into the underlying rocks and infilling by quartzite, and the similarity to the same stratigraphic position recognized at the White Swan Mine.

Sequence 3

Sequence 3 is thickest at Willow Springs (42 m) and generally thins to the southeast and northwest. At Badger Flat, Sequence 3 is 38.5 m thick, at Johnson Spring, it is 31.5 m thick, and at the White Swan Mine it is 24 m thick (Plate 1). Systems tracts within Sequence 3 are well-developed and demonstrate classic geometries. This sequence consists of a progradational northwestward-thinning lowstand wedge, a generally southeast-thinning transgressive systems tract, and an aggradational followed by

Figure 43. Sequence Boundary 2 (SB-2) at the base of a laminated quartzite bed in the Badger Flat Limestone at Johnson Spring. Hammer head is 18 cm long.

progradational highstand systems tract of uniform thickness (Fig. 38).

At Willow Springs Canyon, a lowstand wedge is present in the form of mixed carbonates and quartzites (Plate 1). Two quartzite beds are present. The lower is 1.5 m thick and the upper is 0.5 m thick. These quartzites fill incisions up to 0.5 m deep into the underlying carbonates. At the White Swan Mine, reworked clasts with lithologies resembling those in the upper Badger Flat Limestone (Fig. 40), ranging up to 6 cm in size and set in a brown quartzite matrix, are fairly abundant at the base of the Eureka Quartzite. This shallow-water deposit is interpreted to represent the base of a lowstand systems tract.

At Johnson Spring, a 1.5-m-thick quartzite bed 9 m below the contact with the overlying Barrel Spring Formation (Plate 1) is interpreted to represent a lowstand wedge, although it could be interpreted as reworked sand at the base of a transgressive systems tract. This bed consists of very fine-grained, laminated quartzite with minor bioturbation near the top. Minor incision into the underlying Mottled Carbonate Facies of Sequence 2 averages less than 1 cm. At Badger Flat a single 2.8-m-thick, massive quartzite bed 10.5 m below the contact with the overlying Barrel Spring Formation is interpreted to represent the same lowstand deposit.

Overlying the lowstand systems tract deposits is a well developed, generally southeast-thinning transgressive systems tract (Fig. 38). At Johnson Spring, the deepening event that produced this succession is shown by a vertical change in the Barrel Spring Formation from the Mottled Carbonate Facies to the Silty Carbonate Facies, upward into the Siltstone and Black Shale Facies (Plate 1). The Black Shale Facies, one

of the deepest water facies in rocks of this age, contains graptolites that are generally considered to represent offshore marine environments (Ross, 1966).

At the White Swan Mine section, half of the 12-m-thick, gray, impure, thin-bedded, burrowed quartzite in the Eureka Quartzite 11.5 m above the contact with the underlying Badger Flat Limestone represents a transgressive systems tract. These rocks probably represent an intertidal to subtidal environment and are interpreted to be equivalent to the Barrel Spring Formation and underlying carbonates of the upper Badger Flat Limestone in Mazourka Canyon.

At the Willow Springs Canyon section, the transgressive systems tract includes the uppermost 31 m of the Badger Flat Limestone and extends 7 m into the Barrel Spring Formation. In this location the transgressive systems tract consists of six thin-bedded quartzites that are interbedded with five carbonate beds typical of the Massive Carbonate and Thin-bedded Limestone Facies. These rocks are overlain by 4 m of Barrel Spring Formation siltstone which in turn is overlain by 2.4 m of Black Shale Facies similar to that at Johnson Spring. These rocks are interpreted to represent a retrogradational parasequence set and the Black Shale Facies is considered the deepest water facies in this systems tract. At the top of the section at Willow Springs Canyon the Siltstone Facies reappears which represents the highstand systems tract (Fig. 6).

In the Badger Flat section, the transgressive systems tract is represented by the upper 9.5 m of the Badger Flat Limestone and lower 22 m of the Barrel Spring Formation. The lithologic change from interbedded Silty Carbonate Facies and Thin-bedded Limestone Facies to brown Siltstone Facies is interpreted to represent an upward-

deepening event and a landward shift in facies similar to that elsewhere in Mazourka Canyon (Plate 1). Four quartzite beds are present in the upper part of the Barrel Spring Formation. These are not observed at the Johnson Spring section but are possibly related to the six quartzite beds in the upper Badger Flat Limestone at Willow Springs Canyon.

The top of the transgressive systems tract is marked by Maximum Flooding Surface 2. At the White Swan Mine, the position of Maximum Flooding Surface 2 is inferred to occur 18 m above the base of the Eureka Quartzite within the middle of the sequence of impure thin-bedded quartzites in which trace fossils occur. The precise placement of this surface is uncertain, as rocks are very similar both above and below this position. The author, however, placed it in the middle of this unit (Plate 1).

At Johnson Spring and Willow Springs Canyon, Maximum Flooding Surface 2 is placed in the middle of the Black Shale Facies within the Barrel Spring Formation (Fig. 44). At Badger Flat, the exact placement of Maximum Flooding Surface 2 is problematic due to the lack of black shale in the upper part of the Barrel Spring Formation. However, the surface most likely occurs within the top 4 m of the Barrel Spring Formation in the same stratigraphic position as in the adjacent Johnson Spring section. It is possible that Maximum Flooding Surface 2 merges to the northwest with the overlying sequence boundary (Sequence Boundary 3) due to erosion along that surface.

In the Johnson Spring section, the highstand systems tract is interpreted to include the upper 2.4 m of the graptolitic Black Shale Facies of the Barrel Spring Formation and the overlying Siltstone Facies typical of the Barrel Spring Formation (Fig. 7). In the White Swan Mine section, the highstand deposits are most likely represented by the

Figure 44. Maximum Flooding Surface 2 (MFS-2) and Sequence Boundary 3 (SB-3) at Willow Springs Knob. SB-3 separates the Barrel Spring Formation from the overlying Johnson Spring Formation.

upper part of the impure, thin-bedded quartzite beds. At Willow Springs Canyon the highstand systems tract is made up of a shallowing-upward sequence consisting of 1.1 m of the Black Shale Facies overlain by 6 m of Siltstone Facies in the upper Barrel Spring Formation (Fig. 44).

The highstand systems tract in Sequence 3 thins slightly to the northwest, and is very thin at Badger Flat, most likely due to erosion, which may have removed the Black Shale Facies. Typical of all but the Badger Flat section in Mazourka Canyon, aggradation in the Black Shale Facies is followed by progradation of the overlying Siltstone Facies.

Sequence Boundary 3 is a well-developed disconformity that defines the top of Sequence 3. This surface separates the highstand deposits of Sequence 3 from the lowstand deposits at the base of Sequence 4. At Johnson Spring, this surface, Sequence Boundary 3, is quite irregular (Fig. 45) and represents up to 5 m of incision into the Barrel Spring Formation. At the base of the Johnson Spring Formation in Willow Springs Canyon, minor incision below Sequence Boundary 3 into the underlying siltstone of the Barrel Spring Formation is observed. At the Badger Flat section, Sequence Boundary 3, placed at the base of the lowest quartzite bed (1.2 m thick) of the mapped Johnson Spring Formation (Ross, 1966), shows little or no incision into underlying rocks.

In the Talc City Hills, a marked change in lithology is interpreted to represent Sequence Boundary 3. Impure thin-bedded quartzites of the highstand systems tract of Sequence 3 are overlain with a sharp contact by the higher, massive, cliff-forming part of the Eureka Quartzite interpreted to represent the base of Sequence 4 (Plate 1).

Figure 45. Sequence Boundary 3 (SB-3) at Johnson Spring, separating the Barrel Spring Formation from the Johnson Spring Formation.

Sequence 4

Sequence 4 is thickest at Willow Springs Canyon (150 m) and thins significantly to the northwest at Johnson Spring (101 m) and Badger Flat (34 m). It thins only slightly to the southeast at the White Swan Mine (130.5 m). Sequence 4 consists of a progradational, northwest-thinning, lowstand systems tract, a transgressive systems tract that displays an overall northwest-thinning, and a highstand systems tract that generally thins to the northwest.

The rocks within the lowstand systems tract at Willow Springs Canyon and Badger Flat display an overall thickening upward of beds of the nearshore Quartzite Facies (Plate 1) typical of a progradational lowstand wedge (Van Wagoner et al., 1988). A 1-m-thick conglomeratic bed composed of quartzite lithoclasts ranging from 1 to 6 cm in diameter in an impure quartzite matrix is present at the base of the lowstand systems tract at the base of the Johnson Spring Formation at the Willow Springs section. Three pure quartzite beds interbedded with siltstone overlie the conglomeratic bed and thicken upward from 1 m to 1.5 m. Overlying these beds is a 13-m-thick bed of pure massive quartzite. The basal conglomerate appears to truncate the underlying siltstone and fill scours up to 0.5 m deep.

At Johnson Spring the lowstand deposit is represented by a massive quartzite unit at the base of the Johnson Spring Formation. Although the thickening-upward stacking pattern observed at Willow Springs Canyon is not observed at Johnson Spring, this deposit is interpreted to represent the same interval. This is based on both the stratigraphic position at the base of the Johnson Spring Formation and the incision up to 5

m into the underlying siltstone of the Barrel Spring Formation and subsequent infilling by quartzite (Fig. 45).

At Badger Flat the lowstand systems tract is represented by interbedded quartzite and carbonate-rich siltstone. Four quartzite beds too thin to show individually on Plate 1 were observed within this interval. The lower two are 0.75 m thick whereas the upper two are 1.2 m thick. The four quartzite beds are separated by siltstone beds and display a distinctive upward thickening of the near-shore Quartzite Facies characteristic of progradational stacking. Lack of exposure prevents direct observation of the nature of Sequence Boundary 3 at Badger Flat.

In the Talc City Hills a lowstand systems tract is not recognizable. However, here it is inferred based on comparisons with the sections in Mazourka Canyon (Fig. 38). The entire lowstand deposit is placed within a 16.5-m-thick, massive quartzite bed 23.5 m above the base of the Eureka Quartzite as mapped by Hall and MacKevett (1962).

Overlying the lowstand systems tract and separated from it by a transgressive surface (Transgressive Surface 3) is a well-developed, generally northwest-thinning, transgressive systems tract that indicates a deepening event typical of onlap deposits. This systems tract extends through the Johnson Spring Formation and correlative Eureka Quartzite into the overlying Ely Springs Dolomite.

Retrogradational facies stacking observed throughout Mazourka Canyon represents an overall stacking pattern typical of a transgressive systems tract (Plates 1, 2). At Willow Springs Canyon, onlap deposits are observed within the mixed carbonates and quartzites in the Johnson Spring Formation and the lower member of the Ely Springs

Dolomite. The base of the transgressive systems tract is placed at the base of the lowest carbonate bed, 18 m above the mapped base of the Johnson Spring Formation (Plate 1), described by Ross (1966) as the Mixed Lithology Member. This member is 31 m thick and consists of five quartzite beds ranging in thickness from 1 to 5 m, interbedded with carbonates representative of several different facies (Plate 1). The lower part of the transgressive system tract shows an overall upward thinning of the quartzites. In this interval, the carbonates also thicken upward at the expense of the quartzites (Plate 1). The contact at the base of each quartzite bed is commonly irregular and has up to 0.5 m of incision into the underlying rocks.

Overlying the Mixed Lithology Member of the Johnson Spring Formation at Willow Springs Canyon are two retrogradational parasequences. The lower parasequence consists of 19.2 m of clean quartzite typical of the Johnson Spring Formation, overlain by 8 m of thin-bedded dolomite with intermixed oncolites 2 m from its top. Overlying this parasequence is the second parasequence consisting of 16 m of massive quartzite in turn overlain by 20.5 m of the lower member of the Ely Springs Dolomite.

At Johnson Spring, the transgressive surface is placed at the top of the lowest quartzite bed within the mapped Johnson Spring Formation. Directly overlying this surface is the Mixed Lithology Member (Ross, 1966). The six quartzite beds in the Mixed Lithology Member do not display any vertical pattern of thickening or thinning. Thin-bedded limestone is abundant, and contacts with overlying quartzites show no or little incision. Overlying the Mixed Lithology Member are two parasequences (9.5 m and 16 m thick, respectively) consisting of basal shallow-water quartzites with overlying deeper

water carbonates (Plates 1 and 2). The upper quartzite bed is thinner than the underlying bed, typical of a deepening event related to a marine transgression (Van Wagoner et al., 1988).

At Badger Flat, Transgressive Surface 3 is placed at the top of the higher of two quartzite beds, both of which are considered lowstand deposits. The overlying brown siltstone and carbonate beds are here correlated with the Mixed Lithology Member to the southeast (Plate 1). Overlying the siltstone is 15 m of quartzite similar to that near the top of the Johnson Spring Formation at Johnson Spring and interpreted to represent part of the truncated transgressive systems tract. Any higher beds that may have been deposited have been eroded away during the development of Sequence Boundary 4.

In the Talc City Hills the transgressive systems tract is difficult to define due to the underlying sequence of unbroken quartzite. Transgressive Surface 3 is placed at the base of a 3.5-m-thick siltstone bed 40.5 m above the base of the mapped Eureka Quartzite. This surface is placed here because the siltstone is interpreted to represent a flooding event. The overlying quartzite is overlain by the lower member of the Ely Springs Dolomite, into which the transgressive systems tract appears to continue.

Throughout Mazourka Canyon, the transgressive systems tract is well displayed. The transgressive systems tract of Sequence 4 at Willow Springs Canyon includes an aggradational parasequence set (Fig. 46). Some of the quartzites are interpreted to be reworked sediment from the underlying lowstand systems tract. In the Talc City Hills, correlation of the transgressive systems tract is difficult and based mostly on stratigraphic

Figure 46. Mixed Lithology Member of the Johnson Spring Formation of Ross (1966) at Willow Springs Canyon.

position, a basal siltstone just above Transgressive Surface 3, and the overlying Ely Springs Dolomite, the lower part of which is assigned to the transgressive systems tract (Fig. 38).

Overlying the transgressive systems tract above Maximum Flooding Surface 3 are deposits of the highstand systems tract of Sequence 4. At the White Swan Mine, Maximum Flooding Surface 3 is placed within the lower member of the Ely Springs Dolomite, 11.5 m above the contact with the underlying Eureka Quartzite, based on the presence of abundant chert (Cherty Carbonate Facies). Based on the abundance of chert, this interval is thought to represent the deepest water deposits (Stevens, 1991).

At Willow Springs Canyon and Johnson Spring, Maximum Flooding Surface 3 is placed at a stratigraphic position similar to that in the Talc City Hills. At both locations, the lower member of the Ely Springs Dolomite contains the Cherty Carbonate Facies. This interval is not present at Badger Flat, where it was apparently removed by erosion during the formation of Sequence Boundary 4 (Fig. 38).

The highstand systems tract is thickest at the White Swan Mine (37.5 m) and thins to the northwest, pinching out between Johnson Spring, where it is 19.5 m thick, and Badger Flat. At Willow Springs Canyon the 35.5-m-thick systems tract is well developed. The highstand deposits, contained within the lower member of the Ely Springs Dolomite, are represented by massive dolomite and chert stringers with several 1-m-thick boundstone beds. These rocks are overlain by 5.5 m of the dolomitic Oncolitic Facies and 4.5 m of massive dolomite (Plate 2).

At Johnson Spring the highstand systems tract is represented above Maximum Flooding Surface 3 by 3.5 m of Cherty Carbonate Facies and Massive Carbonate Facies overlain by dark-gray dolomite with abundant chert nodules. In the Talc City Hills, the highstand is present 11 m above the base of the Ely Springs Dolomite, with a basal chert-rich interval 4 m thick, overlain by 19 m of the typical lower member of the formation, which is overlain by 15.5 m of dolomitic Oncolitic Facies interbedded with Cherty Carbonate Facies. The difference in thickness of the oncolitic dolomite at this location compared to the 5.5-m-thick deposit at the top of the highstand systems tract at the Willow Springs Canyon is interpreted to represent the basinward progradation of this facies.

Overall, the highstand systems tract in Sequence 4 thins substantially to the northwest and is not recognized at Badger Flat, due to erosion related to the overlying sequence boundary (Sequence Boundary 4). At the White Swan Mine and Willow Springs sections, facies show a shallowing-upward pattern within the lower member of the Ely Springs Dolomite, a characteristic of highstand deposits (Handford and Loucks, 1993).

Sequence Boundary 4 is a well-developed disconformity that defines the top of Sequence 4. At Badger Flat, this surface is at the top of the Johnson Spring Formation and separates the transgressive deposits of Sequence 4 from the lowstand wedge at the base of Sequence 5 (Fig. 38). At all other locations, Sequence Boundary 4 separates the highstand systems tract deposits of Sequence 4 from the overlying transgressive systems tract of Sequence 5.

Sequence Boundary 4 is well exposed at Willow Springs Canyon and is placed near the contact between the lower member of the Ely Springs Dolomite and the overlying middle member, 56.5 m above the contact between the Ely Springs Dolomite and the underlying Johnson Spring Formation (Ross, 1966). The surface is irregular and displays up to 1 m of relief (Fig. 47). A few meters below Sequence Boundary 4 are breccias containing clasts of the overlying middle member and the top of the lower member of the Ely Springs Dolomite (fig. 48). Clasts are angular, poorly sorted, and range in size from 2 to 14 cm. Clasts that were derived from the middle member are white to light-brown, massive dolomite. Clasts that were derived from the lower member are gray, oncolitic dolomite. Abundant oncolites range in size from 0.5 to 2 cm in diameter and commonly are selectively preserved as clasts within the breccia. The matrix is similar to that of the gray oncolitic dolomite in the top of the lower member. The cavities consist of enclosed, irregular, funnel shapes up to 1.5 m deep, previously described by Miller (1976) as localized features which he interpreted to be storm or channel deposits. It is unlikely that these breccias are related to either storms or channelization because the clasts contained within the matrix originated from strata up to 5 m up section. Storm and channel deposits would consist of clasts ripped up from underlying strata. These deposits of surface and subsurface accumulations of discrete carbonate breccia probably formed by the collapse of cave roofs (Esteban and Klappa, 1983) and are here interpreted to be due to karstification and roof collapse.

Figure 47. Sequence Boundary 4 (SB-4) and solution cavity in the Ely Springs Dolomite at Willow Springs Canyon. Plants are about 20 cm tall.

Figure 48. Karst breccia in the lower member of the Ely Springs Dolomite at Willow Springs Canyon. Pocket knife is 10 cm long.

At the White Swan Mine section, Sequence Boundary 4 is placed at a stratigraphic position similar to that at Willow Springs Canyon, about 2 m above the base of the middle member of the Ely Springs Dolomite (Plate 2). In this section, a breccia contains clasts ranging from 5 cm to 1 m in diameter (Figs. 49, 50). The clasts, which consist of light-colored dolomite typical of the middle member, and oncolitic dolomite similar to that in underlying lower member, occur in a dolomitic matrix. This breccia is interpreted to have formed in a fashion similar to that of the breccia in Willow Springs Canyon. Sequence Boundary 4 in the Talc City Hills is placed directly above the breccia zone, about 4.5 m above the base of the middle member of the Ely Springs Dolomite (Plate 2).

In Mazourka Canyon at Johnson Spring, Sequence Boundary 4 is placed 2 m above the contact between the lower and middle members of the Ely Springs Dolomite (Plate 2). At this locale, a breccia, only a few centimeters thick, overlies this contact. Unlike the breccia in the Talc City Hills and Willow Springs Canyon, these clasts appear to have originated from the dark-colored dolomite beds below Sequence Boundary 4 and may represent the basal conglomerate of Sequence 5.

At Badger Flat, Sequence Boundary 4 is placed at the contact between breccias in the Ely Springs Dolomite and the underlying Johnson Spring Formation (Fig. 38). In this section approximately the upper 1/3 of the Johnson Spring Formation appears to be missing. Ross (1966) presented measured sections indicating an overall northwest thinning of the Johnson Spring Formation and the pinch out of the upper quartzite unit. Evidence that this is due to erosion includes the presence of a thick breccia deposit

Figure 49. Karst breccia below Sequence Boundary 4 (SB-4) at the White Swan Mine. Center of figure is enlarged below.

Figure 50. Large clast in karst breccia in the Ely Springs Dolomite at the White Swan Mine. Hammer is 35 cm long.

containing both quartzite clasts and clasts of Ely Springs Dolomite immediately above the Johnson Spring Formation.

Sequence 5

Due to the scope of this study only the lower part of Sequence 5, the lowstand and transgressive systems tracts, is described here. Overlying Sequence Boundary 4 at Badger Flat is a well-developed lowstand wedge within the middle member of the Ely Springs Dolomite (Fig. 38). This deposit thins dramatically to the southeast. Overlying this deposit and separated from it by Transgressive Surface 4 is the transgressive systems tract of Sequence 5.

The 17.5-m-thick lowstand systems tract at Badger Flat records a southeast-thinning lowstand wedge. Three types of breccia are present within this lowstand deposit. Above the top of the Johnson Spring Formation, this wedge is marked by 1.3 m of breccia containing quartzite, gray dolomite, and abundant black chert clasts up to 7 cm in diameter, in a quartz-sand matrix. Overlying this breccia is a second breccia, 11.6 m thick, which differs from the underlying deposit in that the matrix is dolomitic (Fig. 51). Clasts up to 10 cm are similar in lithology to the underlying breccia, but are more angular and larger than those in the underlying breccia. Based on lithology, these clasts appear to have originated from the lower member of the Ely Springs Dolomite.

In the upper 4.6 m of the lowstand deposit at Badger Flat is a breccia composed of angular black chert clasts up to 30 cm in diameter set in a black chert matrix. All three of

Figure 51. Dolomite and chert clasts in a dolomitic matrix in the basal Flv

these breccias are considered to represent subaerial deposition with an overall northwest progradation and are thought to be related to a localized uplift. This uplift most likely occurred sometime in the latest Ordovician.

At Johnson Spring, Sequence 5 overlies a conglomeratic bed less than 0.5 m in total thickness and composed of chert and dolomite clasts ranging from 1 to 4 cm in diameter. At Willow Springs, a very similar breccia is observed 1.5 m above Sequence Boundary 4. Black chert clasts 1 to 4 cm in diameter are contained within a gray dolomitic matrix.

At the White Swan Mine, the middle member of the Ely Springs Dolomite, 76 m thick, consists mostly of massive dolomite and oncolitic dolomite and is overlain by the deep-water Cherty Carbonate Facies deposits at the base of the upper member. Thus, a well-developed transgressive systems tract recording a deepening event is reflected in the retrogradational stacking of deeper-water facies over shallow-water facies; higher in the section, however, the shallow-water Oncolitic Facies becomes prominent (Plate 2).

At Willow Springs Canyon and Johnson Spring the transgressive systems tract of Sequence 5 is represented by the middle and upper members of the Ely Springs Dolomite. At Willow Springs Canyon, this systems tract consists of massive dolomite (35 m) and sandy dolomite (36.5 m) within the middle member and the upper member, which includes the Black Chert Facies. At Badger Flat the transgressive systems tract consists of 26 m of mostly thin-bedded dolomite of the Boundstone Facies typical of the middle member of the Ely Springs Dolomite and 10 m of thin-bedded carbonate overlain by thick-bedded Cherty Carbonate Facies and Massive Carbonate Facies of the upper

member. The upper 5 m of the upper member contains 2.6 m of black chert breccia with a gray dolomitic matrix. Overlying these breccias are 2.4 m of black chert breccia with a chert matrix. Based on the angularity and poor sorting of clasts, these breccias are interpreted to be the result of submarine debris flows along the paleocontinental slope as illustrated by Cook and Mullins (1983).

Overlying the Ely Springs Dolomite in Mazourka Canyon are the argillaceous limestones of the Sunday Canyon Formation and the Vaughn Gulch Limestone. These deposits are primarily thin-bedded to laminated, contain transported fossils, and are interpreted as basinal (Stevens, 1991). The contact between these beds and the Ely Springs Dolomite is sharp and probably represents a hiatus. As these formations are not within the realm of this study, they will not be discussed in any more detail.

Sequence Correlations

Correlations of sequence boundaries in the Talc City Hills and Mazourka Canyon are based mostly on the analysis of the sequence stratigraphy and the relative stratigraphic positions. Correlations with sequence boundaries farther east on the platform, however, are somewhat problematic due to abrupt facies changes and large changes in formation thickness. Cooper and Lehnert (2001) recognized nine possible sequence boundaries in the Eastern Assemblage (Fig. 52) that they labeled Surfaces F through N. In the Talc City Hills, Cooper and Keller (1995) recognized seven of those sequence boundaries (F, G, H, J, L, M, and N), based on either karst development or reworking of sediment.

Figure 52. Sequence stratigraphic correlation of Keller and Cooper's (1995) eastern assemblage with the western assemblage of this study represented by generalized stratigraphic columns in the Talc City Hills and Mazourka Canyon.

Cooper and Keller (2001) correlated Surface F, the contact between the Goodwin Limestone and the overlying Ninemile Formation in Death Valley, the Funeral Mountains, the Nopah Range, and the Montgomery Mountains in Nevada, with the contact between the Tamarack Canyon Dolomite and the Al Rose Formation in the Talc City Hills.

Cooper and Keller (1995) recognized Surfaces G, H, I, and J within the Antelope Valley Limestone and correlated them with surfaces within the Badger Flat Formation in the Talc City Hills. These surfaces were placed approximately 50 m, 75 m, 95 m, and 115 m, respectively, above the contact with the underlying Al Rose Formation. Sequence boundaries G, H, and I in the Talc City Hills were described by Keller and Cooper (1995) as in-situ breccias consisting of clast-supported carbonate blocks in a carbonate matrix, below which the fractures are infilled with pure quartz sand. These surfaces were interpreted by Keller and Cooper (1995) to represent periods of subaerial exposure resulting in dissolution of the underlying carbonates, karstification, and later infilling of fractures with quartz sand that was thought to overlie the erosion surface. These surfaces were correlated by Keller and Cooper (1995) to other surfaces at similar stratigraphic positions in Death Valley, the Funeral Mountains, Nopah Range, and the Montgomery Mountains in Nevada. Surface J was recognized by Cooper and Lehnert (2001) as a major unconformity present throughout Death Valley, the Funeral Mountains, Nopah Range, and the Montgomery Mountains in Nevada. In these sections, Cooper and Keller (1995) recognized an intricate network of solution pipes filled with clasts from the upper

part of the overlying Eureka Quartzite in a quartz sand matrix. These pipes reportedly cut down as much as 150 m into underlying strata. Surface J was described as an irregular sharp contact, clearly not of tectonic origin (Keller and Cooper, 1995). Keller and Cooper (1995) also reported paleokarst cavities filled with reddish, fine-grained sand and silt along with incised valleys up to 20 m deep filled with dolomitic boulders derived from underlying strata. Keller and Cooper (1995) recognized this unconformity in the upper part of the Badger Flat Limestone in the Talc City Hills. Based on its stratigraphic position, it may correlate with Sequence Boundary 2 (John Cooper, personal communication, 2001).

Surfaces K and L were recognized by Keller and Cooper (1995) in sections throughout Death Valley, the Funeral Mountains, Nopah Range, and the Montgomery Mountains in Nevada. In the Talc City Hills, Cooper and Lehnert (2001) placed Surface L at the contact between the Badger Flat Limestone and the overlying Eureka Quartzite and Surface M at the contact between the Eureka Quartzite and the overlying Ely Springs Dolomite. Cooper (personal communication, 2001) recognized Surface N in the section near Swansea (Fig. 1), and in Death Valley, the Funeral Mountains, Nopah Range, and the Montgomery Mountains in Nevada.

Of the nine possible sequence boundaries described by Cooper and Lehnert (2001) only three (Surfaces F, L, and N) are here correlated with boundaries recognized in this study. Based on their stratigraphic position, Sequence Boundary 1 and Surface F appear to be good candidates for a correlation. Keller and Cooper's (1995) Surfaces G, H, I, J, and K are not recognized within the study area. A simple explanation for the absence

of most of these surfaces in the study area is the lack of subaerial exposure of strata at this interval due to the relatively deeper water conditions that existed in the study area at this time.

Cooper and Keller's (1995) Surface J has not been recognized in the study area. Sand-filled cavities and pipes observed in the Talc City Hills are interpreted to be directly related to Sequence Boundary 2, which is correlated with Surface L at the base of the Eureka Quartzite rather than an underlying sequence boundary (Cooper and Keller's Surface J). Although no direct conduit was observed between Sequence Boundary 2 and the underlying quartz sand-filled dissolution cavities, the size and roundness of the quartz grains is similar to that of quartz grains in the overlying basal Eureka Quartzite. It is therefore concluded that the basal Eureka Quartzite most likely is the source for the sediment contained in dissolution cavities.

Keller and Cooper (1995) suggested that Surface J, which is not recognized in this study, probably represents the interregional Sauk-Tippecanoe unconformity of Sloss (1963). The most likely position for the interregional Sauk-Tippecanoe unconformity in the study area is at Sequence Boundary 2 because it is the most pronounced unconformity.

Keller and Cooper's (1995) Surface L is an unconformity placed at the contact between the Antelope Valley Limestone and the overlying Eureka Quartzite (Fig. 52). This surface is herein correlated with Sequence Boundary 2, which in the Talc City Hills is placed at the same stratigraphic level. It is inferred that Sequence Boundary 3 recognized in Mazourka Canyon most likely merges with Sequence Boundary 2 (Surface

L) in the Eastern Assemblage rocks. This interpretation would require the upper Antelope Valley Limestone to be subaerially exposed in the east, while the upper Badger Flat Limestone and Barrel Spring Formation were being deposited to the west at Mazourka Canyon.

Keller and Cooper's (1995) Surface M is an unconformity placed at the contact between the Ely Springs Dolomite and the underlying Eureka Quartzite (Fig. 52). This surface was observed by Cooper and Lehnert (2001) throughout Death Valley, the Funeral Mountains, the Nopah Range, and the Montgomery Mountains in Nevada. Surface M is not observed in Mazourka Canyon where the contact between the Ely Springs Dolomite and the underlying Eureka Quartzite appears conformable. An outcrop at Swansea (Fig. 1) between Mazourka Canyon and the Talc City Hills displays a conformable interfingering relationship of Eureka Quartzite and Ely Springs Dolomite. If this surface exists in the Talc City Hills, it was not recognized in this study. This same surface is not observed in Mazourka Canyon, most likely due to deeper-water present at this outboard location.

Keller and Cooper (1995) placed Surface N at an unconformity within the lower third of the Ely Springs Dolomite. Cooper and Lehnert (2001) recognized it throughout Death Valley, the Funeral Mountains, and the Nopah Range. This surface is herein correlated with Sequence Boundary 4 based on its probable age and stratigraphic position (Cooper, personal communication, 2001).

Correlations between this study and those of Keller and Cooper (1995) and Cooper and Lehnert (2001) are problematic and based on stratigraphic position. In order

to gain chronostratigraphic control and assign age brackets to these surfaces, a detailed biostratigraphic study is needed. This study is in progress by J. Cooper, O. Lehnert, and B. Leathem (John Cooper, personal communication, 2001).

CONCLUSION

The measurement and detailed description of the Upper Cambrian (?) to Lower Silurian strata in the western Inyo Mountains and Talc City Hills has resulted in the recognition of 14 facies and four unconformities not previously described. The recognition of unconformities is based on physical evidence of erosion and on facies contrasts. A general sequence-stratigraphic framework was then applied to these patterns. This allowed correlation of unconformities in the stratigraphic section. These unconformities were traced laterally and correlated between four measured sections, allowing for tentative correlation with other previously recognized unconformities farther to the east.

Facies were differentiated based on gross lithology, color, sedimentary structures, bedding thickness, amount and type of terrigenous material present, and types of fossils present. The most important genetic factors related to these facies were considered the depth of water during deposition and the relative distance from the paleoshore. Depositional environments and water depths were then inferred for each of these facies.

The relative water depth and distance from shore in which each facies was deposited were interpreted based on the vertical arrangement of facies. The vertical arrangement of facies was used to determine whether progradational, aggradational, or retrogradational stacking was present. This allowed the assignment of stacking patterns to

systems tracts within five sequences separated by four unconformities not previously described.

The unconformities identified represent important sequence boundaries. The oldest rocks studied belong to Sequence 1, of which only the highstand systems tract at the top of the sequence was studied. This sequence is separated from Sequence 2 by Sequence Boundary 1. Sequence 2 consists of a transgressive systems tract and a highstand systems tract. Directly overlying the highstand systems tract of Sequence 2 is Sequence Boundary 2, which is best developed in the Talc City Hills and is associated with, and overlies, large dissolution cavities filled with quartzite. Sequence 3 consists of a lowstand systems tract, a transgressive systems tract, and a highstand systems tract.

Sequence Boundary 3 separates Sequences 3 and 4. This disconformity marks incision into the underlying highstand systems tracts of Sequence 3 and is best observed at Johnson Spring in Mazourka Canyon. Sequence 3 contains lowstand, transgressive, and highstand systems tracts. The greatest percentage of siliciclastics in the measured sections is contained within the transgressive systems tract in this sequence.

Sequence Boundary 4 appears to occur at the Ordovician/Silurian boundary (Miller, 1975). This is a major unconformity and is represented by dramatic karstification below the surface in the eastern part of the study area. At Badger Flat, this surface appears to represent the greatest erosion, probably from a localized uplift in that area near the Early Paleozoic shelf margin. Breccias observed at this location appear to represent a debris apron deposited along the flank of this uplift. Overlying this surface is Sequence 5,

of which only the basal lowstand systems tract and transgressive systems tract were studied.

The correlation of the four sequence boundaries to the east is somewhat problematic. Cooper and Lehnert (2001) found nine sequence boundaries east of the study area. Of these nine sequence boundaries, three can be directly correlated with those studied here: Surface F to Sequence Boundary 1, Surface L to Sequence Boundary 2, and Surface N to Sequence Boundary 4. The remaining six surfaces that Cooper and Lehnert (2001) described are not recognized in the study area. It is possible that some of these unconformities to the east become correlative conformities in the deeper water deposits of Talc City Hills and Mazourka Canyon, and two unconformities recognized in the Talc City Hills and Mazourka Canyon (Sequence Boundaries 2 and 3) may merge into one to the east.

The regional correlation of unconformities presents numerous challenges; however, understanding the nature of depositional environments and their vertical stacking patterns allows one to better predict the presence of unconformities. Sequence stratigraphy is a powerful tool that can be adapted from the subsurface to outcrop geology and aid in identifying and understanding these complex surfaces.

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NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

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UMI®

Badger Flat

Ely Springs
Dolomite

Johnson Spring Formation

Willow Springs

Talc City Hill

Johnson Spring

Badger Flat

Falc City Hills

Ely Springs
Dolomite

Eureka Quartzite

Badger Flat Limestone

Explanation

Lithologies		
Carbonate Lithologies	Siliciclastic Lithologies	Other Lithologies
Dolomite	Breccia	Talc
Various Interbedded	Conglomerate	

Badger Flat Limestone

Carbonate Lithologies	Siliciclastic Lithologies	Other Lithologies
Dolomite	Breccia	Talc
Various Interbedded Dolomites	Conglomerate	
Cherty Dolomite	Quartzite	
Oncolitic Dolomite	Silty Sandstone	
Sandy Dolomite	Sandy Siltstone	
Silty Dolomite	Calcite Cemented Sandstone	
Dolomite with Fossil Hash	Silica Cemented Sandstone	
Limestone	Cross-Stratified Sandstone	
Various Interbedded Limestones	Siltstone	
Cherty Limestone	Shale	
Oncolitic Limestone	Bedded Chert	
Sandy Limestone	Irregular Contact SB = Sequence Boundary MFS = Maximum Flooding Surface TS = Transgressive Surface	
Silty Limestone		
Limestone with Fossil Hash		

Al Rose Formation

Tamarack Canyon
Dolomite

Al Rose Formation

Tamarack Canyon
Dolomite

MS

SB-1

Limestone

Silty Limestone

Limestone with Fossil Hash

Irregular Contact
SB = Sequence Boundary
MFS = Maximum Flooding Surface
TS = Transgressive Surface

Plate 1. Measured Sections of the Tamarack Canyon Dolomite or Al Rose Formation through the Johnson Spring F

Al Rose Formation

Tamarack Canyon
Dolomite

SB

T

gh the Johnson Spring Formation in Mazourka Canyon and Tamarack Canyon Dolomite through Eureka Quartzite in the Talc C

Thickness in
Meters

ka Quartzite in the Talc City Hills.

Talc City Hills

Hidden Valley
Dolomite

Explanation

Dolomite

Sandy Dolomite

Silty Dolomite

Dolomite with Fossil Hash

SB = Sequence Boundary
MFS = Maximum Flooding Surface
TS = Transgressive Surface

Ely Springs Dolomite
Upper Member

-230
-225
-220
-215
-210
-205
-200
-195
-190
-185
-180
-175
-170
-165
-160

-170
-165
-160
-155
-150
-145
-140
-135
-130
-125
-120
-115
-110
-105
-100

Willow Springs

Ely Springs Dolomite
Upper Member
Vaughn Gulch
Limestone

Johnson Spring

Ely Springs Dolomite
Upper Member
Sunday Canyon
Formation

Badger Flat

Ely Springs Dolomite
Upper Member
Sunday Canyon
Formation

105 100 95 90 85 80 75 70 65 60 55 50 45 40 35

Plate 2. Measured sections of the Ely Springs Dolomite in Mazourka Canyon and the Talc City Hills.