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PART ONE

EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

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PROTEROZOIC TO RECENT STRATIGRAPHY, TECTONICS, AND VOLCANOLOGY, UTAH, NEVADA, SOUTHERN IDAHO AND CENTRAL MEXICO

Edited by

Paul Karl Link and Bart J. Kowallis

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CONTENTS

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.

Middle: Lake Bonneville shorelines west of Brigham City, Utah.

Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Late Ordovician Mass Extinction: Sedimentologic, Cyclostratigraphic, and Biostratigraphic Records from Platform and Basin Successions, Central Nevada

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ABSTRACT

An exceptional Upper Ordovician–Lower Silurian stratigraphic section was recently discovered in outcrops of the Vinini Formation in the Roberts Mountains, Nevada. It is the only section known anywhere in the world where an investigation can be carried out that relates carbonate $\delta^{13}C$ changes to biotic extinctions and re-radiations and to sea-level changes. In addition, the paleontological, sedimentological, and geochemical records of the deep-marine, lower slope to continental rise depositional facies of the Vinini Formation can be compared closely to that of a coeval stratigraphic succession at Copenhagen Canyon in the Monitor Range of Nevada that represents a shallower, outer shelf to shelf margin depositional setting. This project marks the first time that very different Late Ordovician facies within the same depositional basin can be compared directly using extensive and diverse stratigraphic records. It provides the opportunity to address the question of whether or not fluctuations in biological productivity and potential changes in atmospheric pCO_2 coincided with the beginning and end of the Late Ordovician glaciation interval. It is a remarkable opportunity for a diverse scientific team to explore fundamental relationships in global earth systems.

INTRODUCTION

Stratigraphic sections at Vinini Creek in the Roberts Mountains, at Martin Ridge and Copenhagen Canyon in the Monitor Range, and at Lone Mountain display distinct records of the late Ordovician extinction and associated glacio-eustatic and paleoceanographic events. The extinction interval at Vinini Creek is in the uppermost Vinini Formation, in shale, mudstone, and lime mudstone beds that accumulated in a deep-basinal, lower slope to rise depositional setting. Correlative carbonate strata deposited in intra-platform basin and in shallow-water mid platform settings are represented at the Monitor Range and Lone Mountain sections, respectively, by the uppermost Ordovician to lowest Silurian Hanson Creek Formation. The Vinini Creek section provides continuous records of lithostratigraphy, chemostratigraphy, and biostratigraphy of graptolites, conodonts, and organic-walled microfossils across the extinction interval. These records can be correlated into those of the Hanson Creek Formation, allowing for a direct comparison of varied biotic, sedimentological and geochemical events between a range of depositional environments from platform to deep basin. These environments were situated across a continental margin that was within the tropical latitudinal belt, faced northwestward, and was bathed by warm, nutrient rich seas. Accordingly, the central Nevada sections provide an outstanding opportunity for collecting data sets critical for addressing the cause and effect relationships of paleoclimatic, paleoceanographic, and biotic events associated with the late Ordovician mass extinction.

The central Nevada sections are actively being studied, with support from the National Science Foundation, by a multidisciplinary team that includes S.C. Finney (graptolite biostratigraphy, regional geology), W.B.N. Berry (graptolite biostratigraphy, graptolite extinction and recovery, paleoceanography), J.D. Cooper (sedimentology, sequence stratigraphy), W.C. Sweet (conodont biostratigraphy), S.R.

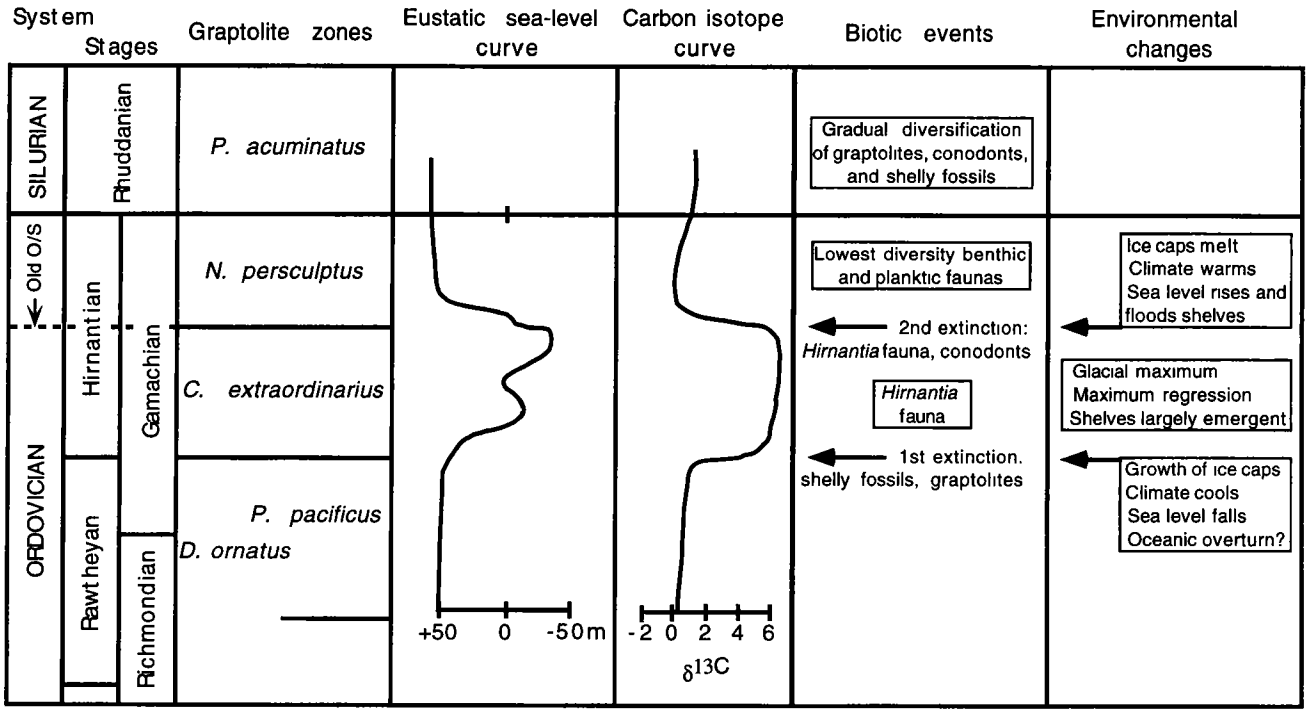


Figure 1. Summary diagram of biotic and environmental changes in Late Ordovician. Modified from Berry et al. (1995) and Brenchley (1988, 1989).

Jacobson (acritarch biostratigraphy, organic geochemistry), R.B. Ripperdan (carbon-isotope stratigraphy), and A. Soufiane (chitinozoan biostratigraphy). The Vinini Creek and Monitor Range sections have been examined and sampled thoroughly. The Vinini Creek section was excavated by a bulldozer. Excavation, description, and sampling were supported by a large team of undergraduate students. At the time of preparation of this paper, considerable sample analyses and identification work have been completed.

THE LATE ORDOVICIAN EXTINCTION EVENTS AND PERTURBATIONS

Globally the Late Ordovician mass extinction reduced species diversity more than 50%. It has been linked to the expansion of Gondwanan ice sheets, global cooling and the restriction of climatic belts, a prominent eustatic sea level fall and subsequent rise, and changes in patterns of oceanic upwelling, nutrient abundance, and water chemistry (Brenchley, 1988; 1989). Stenotopic faunas that became entrenched after millions of years of environmental stability were decimated by rapid perturbations involving multiple earth systems. For example, sharp excursions in the isotopic composition of marine carbon suggest massive disruption of the carbon cycle, and sedimentological evidence indicates the waxing and waning of a major glacial episode and attendant sea-level fluctuations. Although poorly defined, critical relationships between various biologic and secular changes are becoming better known through detailed investigations of stratigraphic sections worldwide.

The central Nevada sections are unique in that a wealth of varied and extensive data sets and information has been collected systematically and interpreted with an integrated multidisciplinary approach.

Beginning with Berry and Boucot (1973) and Sheehan (1973), who first drew attention to a possible relationship between Late Ordovician glaciation and faunal turnover, the nature, extent and temporal correlation of biotic events and associated environmental perturbations have been documented extensively for many stratigraphic successions worldwide. The most comprehensive recent syntheses (Berry et al., 1995; Brenchley, 1988, 1989; Brenchley et al., 1994, 1995; Middleton et al., 1991) are summarized in Figure 1. From these studies, it appears that the Late Ordovician extinction included two distinct extinction events.

The *C. extraordinarius* graptolite zone, which is coeval with the lower Hirnantian Stage, is the critical interval during which an extended period of warm, stable global climate was abruptly terminated. Gondwanan ice caps grew rapidly at the beginning of the Hirnantian. Global climate cooled, sea level fell, and cold bottom currents may have produced oceanic overturn. The plankton (graptolites, chitinozoans, acritarchs) experienced substantial extinction.

Diverse, endemic benthic communities were replaced in extra-tropical regions by the cosmopolitan, cold-water *Hirnantia* community. During the glacial maximum, carbonate platforms in the tropics were exposed extensively, and their own diverse, endemic benthic faunas, displaced to continental margins, suffered massive extinction. With global warming and retreat of the ice sheets in the mid Hirnantian, sea level rose rapidly and warm water flooded the shelves, producing widespread anoxia. The *Hirnantia* fauna disappeared, and conodonts suffered major extinction. The late Hirnantian and Rhuddanian were times of slow recovery and gradual diversification of both plankton and benthos.

According to the most accepted scenario, the first phase of extinction can be related to climatic deterioration, to cold bottom currents inducing upwelling of nutrients that produced anoxic waters, and to the loss of habitat area accompanying the retreat of shallow shelf seas. The subsequent rapid sea-level rise and development of warm anoxic waters on continental shelves may have generated the second extinction phase.

In recent years, isotopic records have been described for several Upper Ordovician-Silurian sections (Orth et al., 1986; Marshall and Middleton, 1990; Middleton et al., 1991; Long, 1993; Brenchley et al., 1994, 1995). The lower Hirnantian is marked by a large positive shift in $\delta^{13}C$ that indicates either: large amounts of organic carbon were removed from the ocean and buried in sediments; or very high productivity, perhaps driven by increased upwelling, caused a steep gradient in ocean carbon composition. The extraction of marine organic carbon could have caused a temporary reduction of atmospheric pCO_2, which may have led to a decline in global temperature, triggering Gondwanan glaciation.

Although it seems probable that the Late Ordovician extinction interval was linked with global changes in climate, sea level, oceanic circulation, and water chemistry, the nature of the linkage remains elusive. In fact, it is likely that the two known major extinction events were caused by different combinations of environmental perturbations. Existing databases are too limited and too imprecise to delineate the temporal correlations necessary for a full understanding of mechanistic linkages during this critical interval. In most available stratigraphic sections, the extinction interval is characterized by a scarcity of fossils, by endemic faunas, and by a major hiatus. And for those few sections in which the extinction interval is fossiliferous and largely complete, the inability to correlate with precision between graptolitic oceanic successions and carbonate platform successions previously has hindered integration of diverse stratigraphic records of interrelated biotic, climatic, and oceanographic events.

The central Nevada sections provide an unprecedented opportunity to correlate directly, and with precision, varied biostratigraphic, sedimentological, and geochemical data from both graptolitic oceanic and carbonate platform successions.

GEOLOGIC SETTING

Lower to Middle Paleozoic rocks of central Nevada (Fig. 2) represent two very different stratigraphic successions that are structurally juxtaposed: a deep basinal siliciclastic succession—the western, eugeoclinal facies; and a shallow-shelf carbonate succession—the eastern, miogeoclinal facies. The eugeoclinal facies comprises the Roberts Mountains allochthon (RMA), which was emplaced eastward along the Roberts Mountains thrust onto the coeval autochthonous miogeoclinal succession during the late Devonian to Mississippian Antler Orogeny (Poole et al., 1992; Stewart and Poole, 1974; Stewart, 1980). Exposures of both western and eastern facies are widespread in mountain ranges of central Nevada, especially in the Roberts Mountains, which is the classical area where the structural relationship of the two facies and the existence of the Roberts Mountains thrust were first recognized (Merriam and Anderson, 1942).

The RMA is a complexly deformed assemblage of sandstone, siltstone, shale, chert, greenstone, and limestone that was deposited on the lower slope, rise and basin plain outboard of the western (Cordilleran) margin of Laurentia during Cambrian to Devonian time. Until recently stratigraphic studies of the RMA have been rather limited and localized. This has been the result of structural complexities, poor exposures, scarce fossils, and monotonous lithologies. For the last several years, however, Finney has carefully mapped the rocks and collected graptolites and conodonts, particularly in the Ordovician Vinini Formation of the Roberts Mountains. He has discovered that the structure is reasonably simple over large areas, the rocks can be reliably mapped, fossils are common and in places abundant, and the stratigraphic section can be reconstructed with confidence (Fig. 3) (Finney and Perry, 1991; Finney and Ethington, 1992a, 1992b; Finney et al., 1993; Finney and Berry, 1994; Ethington et al., 1995; Finney et al., 1995a).

All rocks of the upper plate of the Roberts Mountains thrust in the Roberts Mountains were mapped originally as the Ordovician Vinini Formation with Vinini Creek as the type area (Merriam and Anderson, 1942). Subsequently, it was discovered that the RMA in the Roberts Mountains, as elsewhere in central Nevada, includes Cambrian, Silurian, Devonian, and Mississippian strata as well. Nevertheless, the Vinini Formation composes the greatest part of the RMA in the Roberts Mountains. The lower member of the

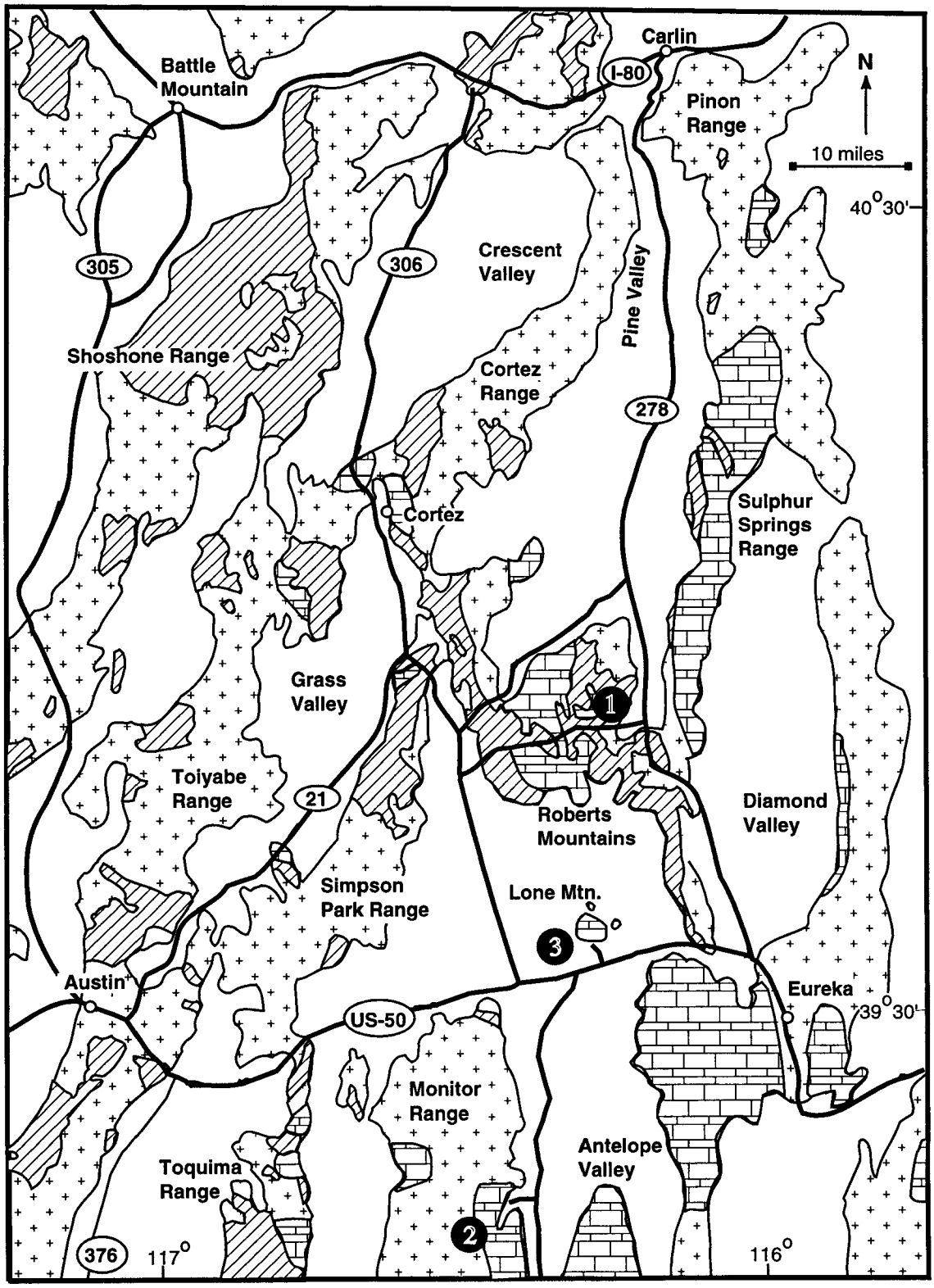


Figure 2. Index map of central Nevada showing field trip ***Stops 1*** *(Vinini Creek in Roberts Mountains),* ***2*** *(Copenhagen Canyon and Martin Ridge), and* ***3*** *(Lone Mountain). Diagonal line pattern shows distribution of outcrops of lower to middle Paleozoic eugeoclinal rocks of Roberts Mountains allochthon. Brick (limestone) pattern represents coeval miogeoclinal rocks. Other rocks in mountain ranges are represented by small cross pattern. They can include Mississippian-Permian post-orogenic rocks, Jurassic plutonic and volcanic rocks, and Tertiary volcanic rocks.*

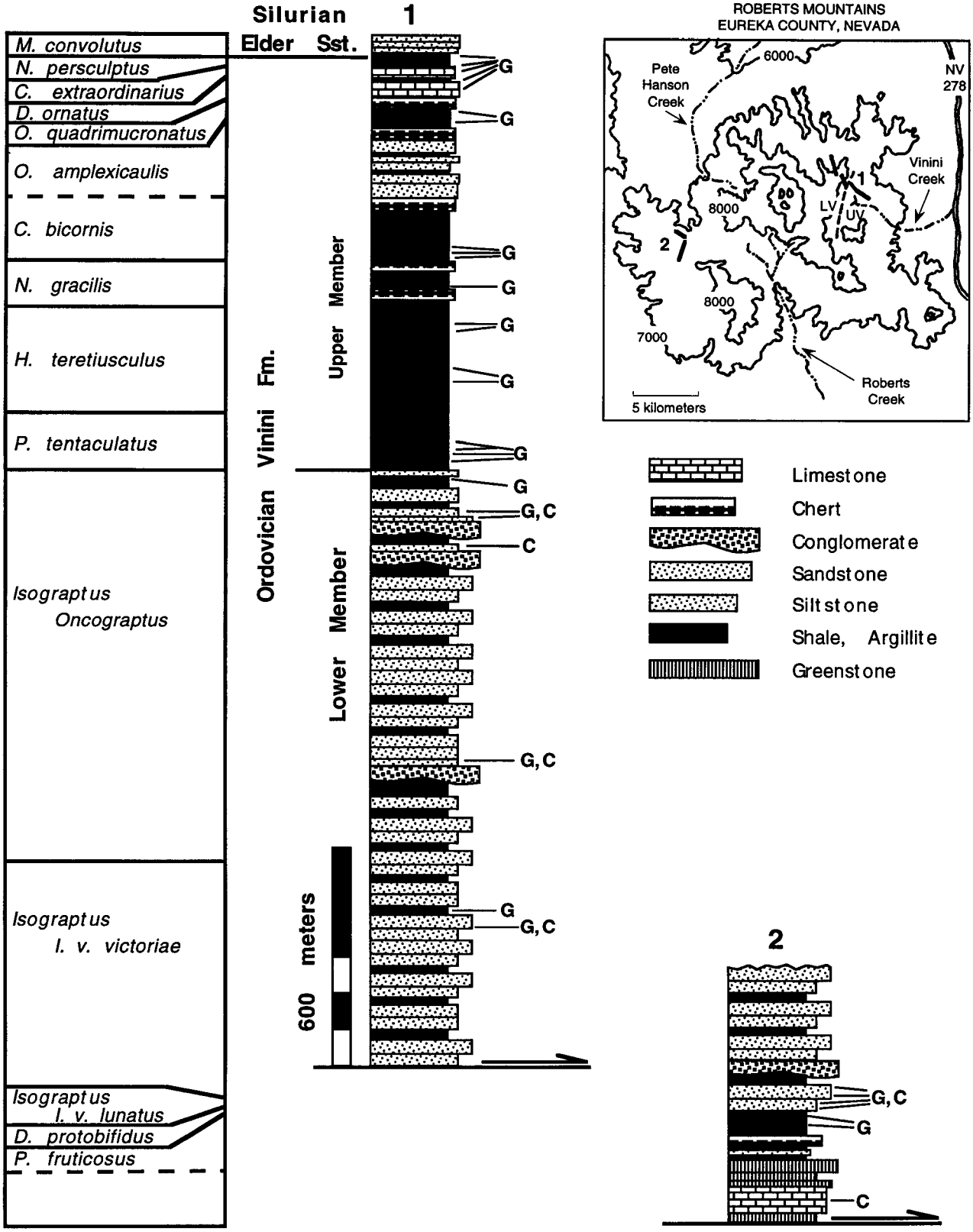


Figure 3. Vinini Creek (1) and Cottonwood Canyon-Red Canyon (2) stratigraphic sections of the Vinini Formation and lowest Elder Sandstone with locations of sections in Roberts Mountains shown in inset map. Left column is graptolite zonation. Stratigraphic levels of important graptolite and conodont collections indicated by G and C. Both sections are at same scale.

Vinini is widely exposed on the west side of the Roberts Mountains. Its oldest biostratigraphically dated rocks are lowest Ordovician, perhaps even uppermost Cambrian, deep-water limestone that is overlain and underlain by thick greenstone hyaloclastite debris flows. These are succeeded by a thick interval of black shale, which, in turn, is overlain by a 1–2 km thick turbiditic, submarine fan facies. A fairly complete stratigraphic succession, including the uppermost lower member of the Vinini (the submarine fan facies), the upper member of the Vinini, and the Silurian Elder Sandstone is exposed along Vinini Creek on the east side of the Roberts Mountains (**Field Trip Stop 1**). Most of the upper Vinini member is shale, argillite, and bedded chert. In contrast, the extinction interval in the uppermost Vinini is composed largely of distinctive lime mudstone beds with very little chert. These, in turn, are succeeded by shale, siltstone, and sandstone of the Silurian Elder Sandstone at the top of the Vinini Creek section.

The miogeoclinal succession is well exposed across Martin Ridge (**Field Trip Stop 2a**) and Copenhagen Canyon (**Field Trip Stop 2b**) in the Monitor Range to the west of Antelope Valley and at Lone Mountain (**Field Trip Stop 3**) at the north end of Antelope Valley (Fig. 4; Merriam, 1940, 1963; Ross, 1970). The Ordovician succession is largely shallow-water carbonate rock except for the upper Ibexian Ninemile Shale and the Mohawkian Eureka Quartzite. The extinction interval is in the upper Ordovician to lowest Silurian Hanson Creek Formation, which is overlain by the Silurian Roberts Mountains Formation. The Hanson Creek Formation represents a carbonate platform depositional setting (Dunham, 1977). In the composite Martin Ridge–Copenhagen Canyon sections, the lower Hanson Creek is largely shaly weathering clayey lime mudstone with abundant, diverse graptolite and conodont faunas. The upper Hanson Creek is composed of poorly fossiliferous, thick-bedded, commonly cherty lime mudstone. At Lone Mountain, the Hanson Creek Formation is entirely dolomite.

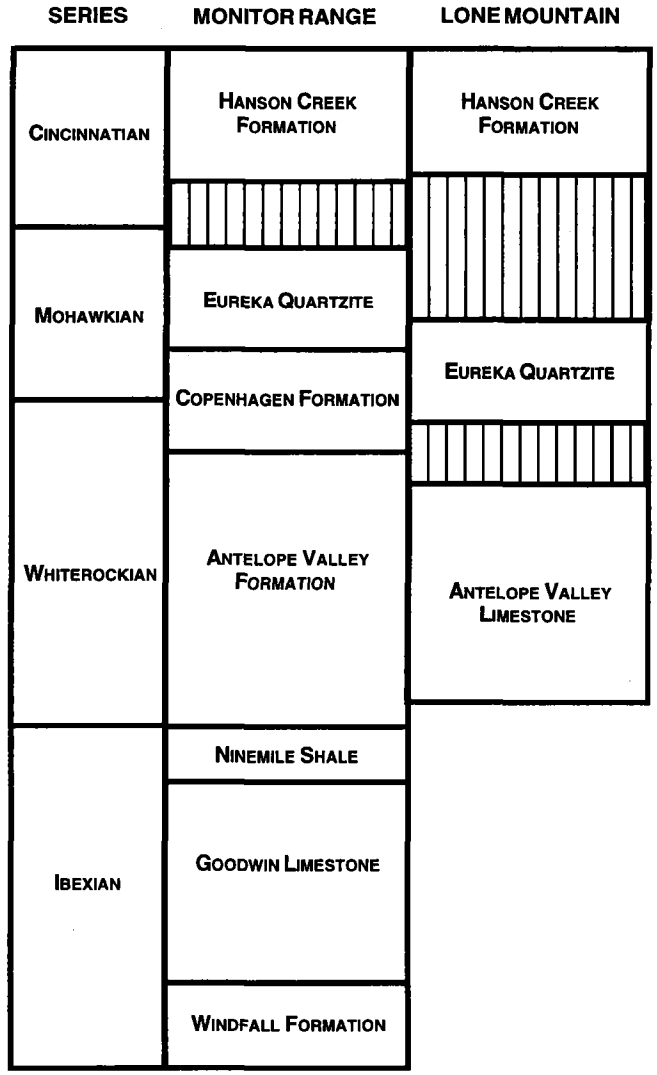


*Figure 4. Correlation of Ordovician stratigraphic successions in Monitor Range (**Field Trip Stop 2**) and at Lone Mountain (**Field Trip Stop 3**), based on Ross (1970).*

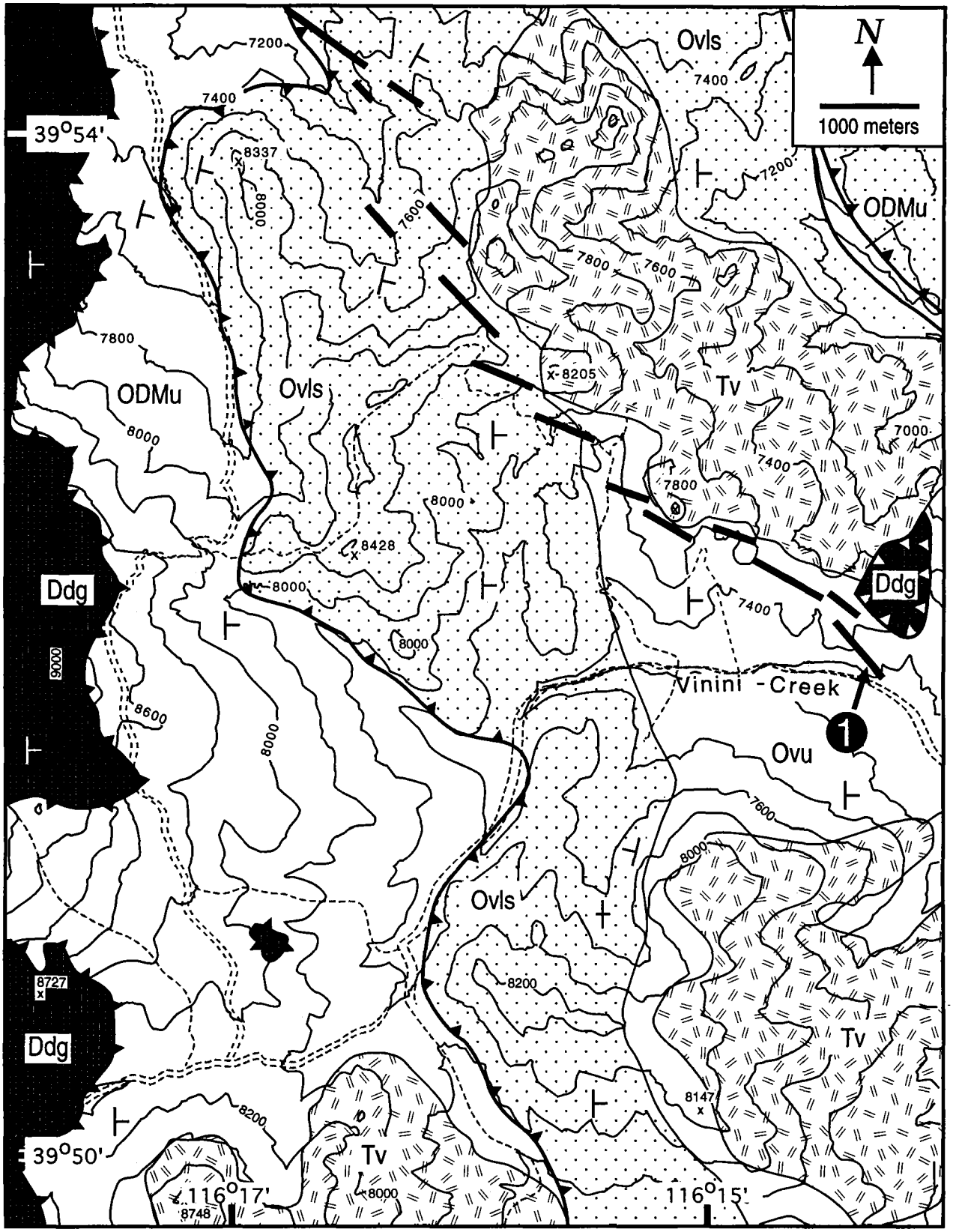
FIELD TRIP STOPS

Vinini Creek Section (V): Trench Excavation—**Field Trip Stop 1**

Overview

The extinction interval occurs in the uppermost part of Finney's (Finney et al., 1993; Ethington et al., 1995) Vinini Creek section that was measured over a distance of 6 km from Dry Creek to Vinini Creek through the upper lower member and the entire upper member of the Vinini Formation and into the lower Elder Sandstone (Fig. 5). The stratigraphic section is 3170 m thick (Fig. 3). The extinction interval, as recorded by graptolites, is at 3050 to 3055 m

*Figure 5. Geologic Map of Vinini Creek area showing location of Vinini Creek section (thick, staggered lines) and **Field Trip Stop 1**. Ddg is Devonian Devils Gate Limestone of lower plate of Roberts Mountains thrust; ODMu is undifferentiated thrust slices composed of, in ascending structural order, Mississippian Webb Formation, Devonian Woodruff Formation, and middle Ordovician Vinini Formation; Ovls is sandstone interval that composes upper half of lower member of Vinini Formation(see Fig. 3); Ovu is upper member of Vinini Formation. Tv is assorted Tertiary siliceous and mafic volcanic rock. Outcrop of Devils Gate Limestone north of field trip stop 1 is a gravity slide block. Contour interval is 200 ft (65 m).*


N
1000 meters
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Vinini Creek
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in the measured section; the Ordovician/Silurian boundary is at 3075 m (Finney et al., 1995b). The extinction and boundary intervals occur on a steep, south facing slope immediately north of Vinini Creek. Here the strata strike north-south and dip steeply to the east. A few resistant limestone and siliceous mudstone beds crop out on the hillside and are exposed in a long-abandoned mine adit at the bottom of the slope. Generally, however, bedrock is buried beneath a 1–3 m thick cover of regolith. The extinction interval and the Ordovician/Silurian boundary were discovered from collections taken from several pits dug through the regolith. With NSF support and permission from the Bureau of Land Management, we contracted for a trench to be excavated by bulldozer down the south-facing slope. The trench was cut as a steep road (Fig. 6). It provides outstanding exposure of the extinction and O/S boundary intervals.

Preliminary sampling indicated that the section, once exposed, would prove to be stratigraphically complete and structurally coherent. That was not the case. The trench section (V) is subdivided into informal subsections VA, VC, and VE, which are separated by zones of structural dislocation VB and VD. In addition, the Ordovician/Silurian boundary is marked by a substantial hiatus. Subsections VD and VE include Silurian rocks that postdate the extinction and recovery intervals and are not illustrated.

Subsection VA (Fig. 7) consists of 19.5 m of interbedded lime mudstone and brown to black shale; graptolites are common throughout. They are of greatest abundance and diversity in an organic-rich interval at 8.5 to 17.5 m in the section. This interval is overlain by 1.5 m of brown siltstone and mudstone in which graptolite diversity is greatly reduced, yet abundance remains high. The highest 0.5 m of VA is lime mudstone with a post-extinction (*C. extraordinarius* Zone) graptolite fauna of few species: *C. extraordinarius*, *N. normalis*, *N. miserabilis*, and two species of *Glyptograptus*. Diversity is low, and abundance, relative to that of the underlying brown interval, is greatly reduced as well.

VB is a zone of structural disruption approximately 5 m thick in which uppermost Ordovician lime mudstone and lowest Silurian shale are folded and dislocated several meters. The limestone and shale are found in normal stratigraphic order in overlying subsection VC.

Subsection VC is 6+ m thick; its upper part gradually becomes highly deformed (Fig. 7). The lowest 4 m is interbedded lime mudstone and laminated mudstone. Carbonate beds thicken upsection. Graptolites are common but not abundant, nor diverse. Graptolites in the lowest 2 m of VC represent the *C. extraordinarius* Zone fauna; those from 2–4 m represent the initial recovery *N. persculptus* Zone fauna. The carbonate beds, representing the top of the

Figure 6. Excavated trench at Vinini Creek section, ***Field Trip Stop 1****. View is to northeast.*

Vinini Formation, are overlain disconformably by lower Silurian olive-green shale and interbedded black chert that are mapped as basal Silurian Elder Formation. Graptolites from thin shale beds 0.5 m above the contact represent the middle Llandovery *M. convolutus* Zone. Much of the lower Llandovery—the lowest seven graptolite zones of the Rhuddanian and lower Aeronian Stages—is missing at the contact between the Vinini and Elder.

VD is a zone, approximately 5 m thick, of highly sheared and folded olive-green Silurian shale and thin chert interbeds. It is succeeded by subsection VE, which is approximately 9 m thick. Olive-green shale grades upsection into beds of fine siliciclastic sediment that thicken and coarsen upsection to siltstone and sandstone. Upper Wenlock graptolites occur in the middle of this interval. The top of the VE is at the top of the trench at the ridge crest.

Subsections VA and VC: Sedimentology

Subsections VA and VC (Fig. 7) include the extinction interval and the Ordovician-Silurian boundary. These subsections are subdivided into nine units based on variations in bundling of limestone and shale beds, lithology, and color (Fig. 7).

Unit VAa (0–1.75 m) consists of thinly interbedded tan-gray lime mudstone and brown-gray weathered mudstone and mudshale. Beds range from 3 to 12 cm thick and the bedded carbonate: fine siliciclastic ratio is approximately 45:55. Some of the lime mudstone beds contain faint to well-developed horizontal lamination. At least a half dozen very thin (0.4–5 cm) grainy layers are present (Fig. 7) and consist of coarse silt to medium sand size grains of carbonate skeletal fragments, including trilobite, ostracode, and echinoderm, as well as phosphatized carbonate

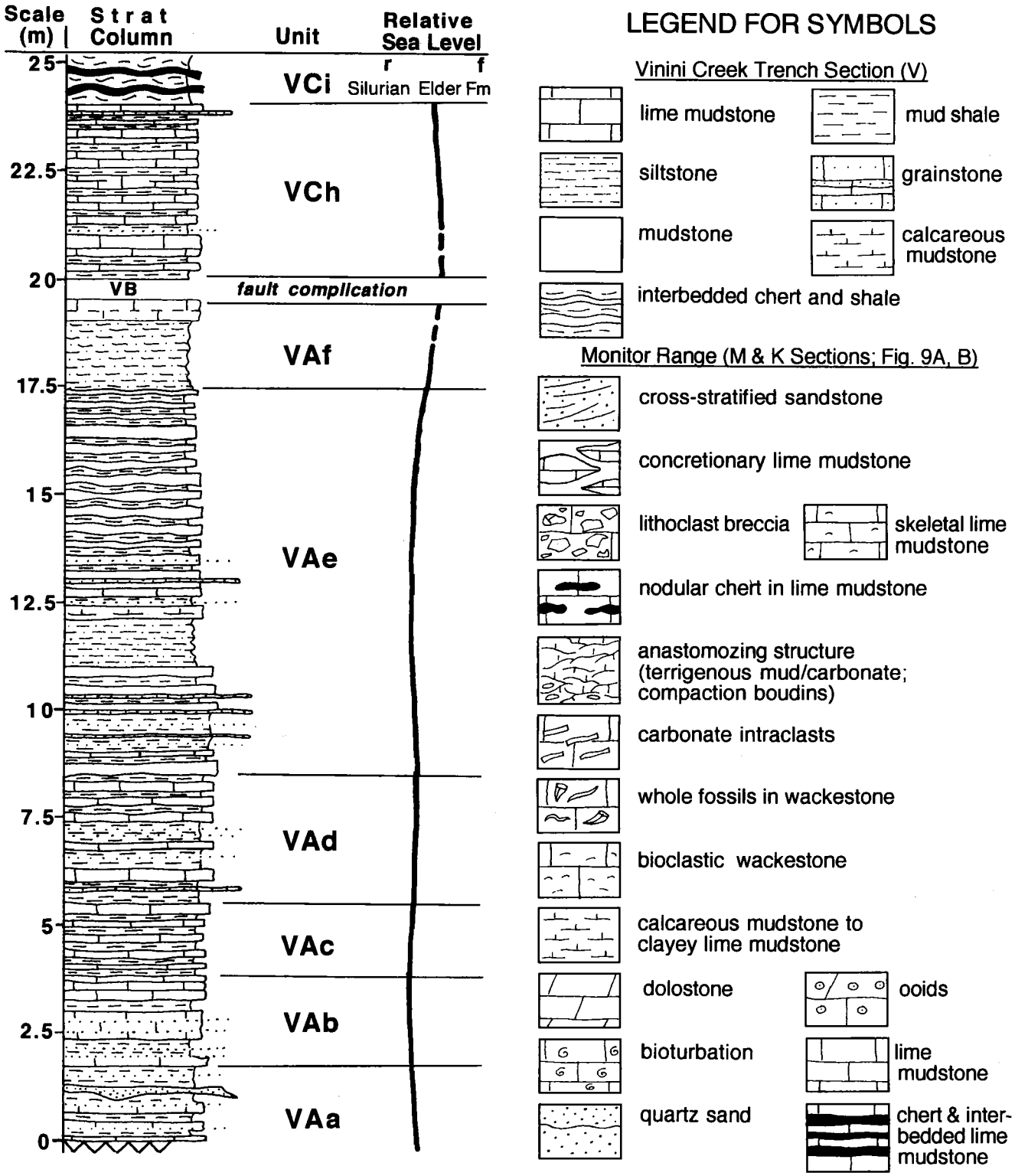

Figure 7. Stratigraphic column, and interpreted sea-level curve, of VA and VC segments of trench exposure of upper part of Vinini Formation, Vinini Creek Section (V), ***Field Trip Stop 1.***

allochems, pellets, and other phosphatic grains, and rare well rounded quartz. Several of these grainy layers contain graptolites, locally in high concentrations.

Unit VAb (1.75–3.8 m) is more calcareous than VAa and consists of three main bundles of tan-gray, thin, impure lime mudstone beds with sub-cm shaly partings, alternating with two 20 to 30 cm-thick dark gray to dark brown mudstone and mudshale beds. This unit is more distinctly packaged than VAa and has a carbonate-siliciclastic ratio of about 65:35. Several mm-thick grainy layers are also present. Lime mudstone beds commonly are laminated, with laminations enhanced by elongate graptolite fragments and flecks of organic detritus.

Unit VAc (3.8–5.5 m) consists of individual gray-tan, 5–15 mm-thick lime mudstone beds rhythmically alternating with thinner (sub-cm partings to 10 cm-thick layers) gray-brown mudstone/shale. Some of the less fissile mudstones show faint color laminations. Carbonate-siliciclastic ratio is about 75:25 and grainy layers are absent.

In unit VAd (5.55–8.55 m), the terrigenous-carbonate ratio is ~60:40. Tan-gray lime mudstone beds 6–12 cm thick are impure and some show faint to distinct color and textural laminations. Laminated mudstone and shale beds are dark brown and several black beds are present near the top. There are some very thin grainstone layers, consisting of skeletal fragments and phosphatic peloids, as well as graptolites and carbonaceous fragments.

The thickest and most distinctive unit is VAe (8.55–17.55 m), which is readily distinguished by its dark gray to black color. VAe is significantly carbonate-poor, containing only a few impure lime mudstone beds in the lower part. The characteristic lithology is 1- to 25-cm-thick beds of blocky weathered, brittle, organic-rich mudstone, with partings to thin (2–13 cm thick) interbeds of dark gray-brown fetid mudstone/siltstone/mudshale. A few very thin grainy layers of fine to medium sandy texture are present in the lower half. Some beds have a pseudo cherty appearance, and in thin section some show a disseminated siliceous component.

Unit VAf (17.55–19 m) is a thin siltstone/mudstone that weathers brown and has a sharp basal contact with underlying unit VAe. This unit becomes progressively more platy bedded to shaly in its upper part.

VAg, as exposed in the trench, is only about 0.5 m thick (19–19.5 m) and consists of medium gray, thin-bedded lime mudstone and interbedded dark gray mudshale. Some of the lime mudstone beds are faintly laminated. This unit is truncated at the top by a fault that juxtaposes Silurian greenish shales of the Elder Formation and Upper Ordovician tan gray lime mudstones. This fault zone is segment VB (Fig. 7).

Unit VCh (subsection C, 0–4 m) begins at the base of coherent section above the underlying fault zone VB, and consists of interbedded lime mudstone and silty clay shale/mudstone (Fig. 7). The impure lime mudstone beds become generally thicker upsection, ranging from 3–10 cm to more than 30 cm thick, with concomitant increase in carbonate:siliciclastic ratio. Lime mudstone beds weather light medium gray and are consistently tan gray on fresh surfaces. Interbedded siltstones/mudstones weather tan to gray brown and some show prominent color laminations. Some laminae sets in the upper part of the unit appear rhythmic and varve-like, with lighter laminations giving stronger reactions to dilute HCl. Several 1–3 cm-thick grainy beds contain phosphatic and carbonaceous peloids; skeletal grains and graptolites are also present. In general, unit VCh is similar to the lower part of the section (units VAa–VAd), especially unit VAb.

Unit VCi (4–6 m) consists of green to brown shale and mudstone, and contorted dark gray, thin (3–10 cm) chert and siliceous mudstone beds of the basal Elder Formation (Fig. 7). Unit VCi rests with sharp contact on the topmost carbonate bed of unit VCh, which shows distinct bleaching and discoloration. Approximately 2 m above the contact, unit VCi becomes highly deformed (subsection VD).

Subsections VA and VC: Depositional Environments and History

The exposed trench section displays features consistent with a deep-water (below storm wave base), quiet-energy, marine depositional setting. The presence of discrete carbonate beds, albeit somewhat impure, clearly indicates accumulation above the Carbonate Compensation Depth (CCD). Lack of bioturbation is evident from preservation of persistent horizontal lamination in both limestone and mudstone/shale beds. This, together with absence of bottom fauna, suggests low-oxygen or dysaerobic bottom conditions, most likely in a lower slope to basin floor setting (Coniglio and Dix, 1993). The pervasive presence of disseminated very fine oxidized organic detritus in the lime mudstones suggests oxidation of organics during the slow settling through the water column (Coniglio and James, 1990).

The fine carbonate-siliciclastic alternations are, for the most part, primary depositional rather than purely diagenetic (*sensu* diagenetic cycles of Hallam, 1986). The presence of color and textural laminations in the carbonate beds reinforces this assertion. Certainly there has been some enhancement of original carbonate and terrigenous mud differences between beds by diagenetic overprinting, whereby some carbonate redistribution modified and augmented the primary bedding rhythm (*sensu* Coniglio and James, 1990). However, according to Einsele and Ricken (1991), rhythmic unmixing, through diagenesis, of a more completely originally homogeneous calcareous terrigenous

sediment (or siliciclastic limestone) is highly unlikely for these kinds of rhythmic alternations.

The carbonate-shale/mudstone apparent cycles probably represent a combination of productivity (carbonate-dominated) and dilution (siliciclastic-dominated) cycles. The default or background sediment was dictated by what was coming into the basin at a particular time because both sediment types were likely extrinsic to the depositional environment. The terrigenous clay and silt might have been contributed as eolian dust from cratonal sources (*sensu* Dalrymple et al., 1985), subsequently redistributed by geostrophic currents and deposited as hemipelagic mud. The carbonate mud likely was delivered to the basin as resedimented periplatform ooze, from an area with a much more robust carbonate factory (i.e., updip subtidal shelf) than could exist in the depositional setting itself. Some carbonate mud may have been delivered as low-density turbid flows. The terrigenous component fluctuated as governed by climatic changes influencing weathering, erosion, and runoff or windborn delivery from the continent. Carbonate mud probably reflects fluctuations in the carbonate factory and delivery influenced by relative sea-level changes, climate, primary carbonate productivity, and storms.

Another factor possibly affecting carbonate/terrigenous ratios could be related to dissolution cycles, most significant for depositional sites within the lysocline and CCD. Dissolution of carbonate could also be related to sites above the lysocline where sediments were relatively rich in organic matter, which provided aggressive CO_2 upon decomposition (Einsele and Ricken, 1991). Such could be the case for black, organic-rich, carbonate-poor unit VAe. Conversely, unit VAe might also reflect a rise in sea level that drowned the platform and thus suppressed the carbonate factory, severely diminishing carbonate sediment input into the basin.

The main sedimentary signal of productivity and dilution, producing carbonate-shale alternations, likely was triggered by Milankovitch orbitally forced precessional cycles amplified by climatic-oceanographic feedback changes (de Boer, 1991). The coarser, thin layers of skeletal (commonly graptolitic) and phosphatic-carbonaceous peloidal grainstones probably were resedimented downslope as grain flow and turbidity flow deposits. They represent depositional "noise" events that periodically punctuated the normal background periplatform to hemipelagic fine-grained sedimentation pattern. These events likely reflect climatic pulses, storms and low amplitude eustatic sea-level falls driven by precessional Milankovitch 5th-order cycles. The abundance of phosphatic grains may reflect resedimentation downslope of carbonate allochems that underwent phosphogenesis during upwelling cycles.

Monitor Range Composite Section (M & K)—**Field Trip Stops 2a, b, c**

Overview

A Middle Ordovician to Lower Devonian stratigraphic succession is exposed in the Copenhagen Canyon area of the Monitor Range (Figs. 4 & 8). The stratigraphic succession strikes north to northeast and dips to the west. The Antelope Valley Limestone, Copenhagen Formation, Eureka Quartzite, and Hanson Creek Formation are well exposed on the eastern flank, the crest, and the western dip slope of Martin Ridge, which forms the east side of Copenhagen Canyon. On the west side of Copenhagen Canyon, the succession includes the upper Hanson Creek Formation, the Roberts Mountains Formation, the Windmill Limestone, and the Rabbit Hill Formation. The lower Hanson Creek Formation is best exposed on the crest of Martin Ridge; the upper Hanson Creek is best exposed in Copenhagen Canyon on the low ridge immediately west of the Copenhagen Canyon road. In our investigation, we found it best to measure, describe, and collect two separate sections in the Hanson Creek Formation (Fig. 8): one on Martin Ridge that is labeled Section M (**Stop 2a**); the other in Copenhagen Canyon that is labeled Section K (**Stop 2b**).

Section M includes the lowest 143 m of the Hanson Creek Formation, which directly overlies the Eureka Quartzite (Fig. 9A). Graptolites, reported by Dworian (1990), are abundant in the lower 120 m of Section M (Fig. 10). The fauna is especially diverse in the interval between 95 to 120 m, which correlates with the *P. pacificus* Subzone of the *D. ornatus* Zone. Above 120 m, where the section is largely lime mudstone beds, graptolites are absent.

The base of section K is at the base of the lowest outcrop of Hanson Creek Formation immediately west of the Copenhagen Canyon road (Fig. 9B). Fossils are scarce or absent in most of the section. Small collections of graptolites were found at four horizons. *Pacificograptus pacificus* was collected at 22 m in section K. Berry (1986) reported *Normalograptus persculptus* at 77 m and *Dimorphograptus confertus* at 108 m. *Rastrites maximus* was reported by Murphy et al. (1979) from a bed at 110 m.

Martin Ridge (Section M—**Stops 2a**): Sedimentology

The lower Hanson Creek Formation at Martin Ridge consists of variations of two main lithologies: bench-forming dark gray lime mudstones and slope-forming gray-brown shaly to platy and thin-bedded clayey lime mudstones and calcareous mudstones. Unit subdivision is based on variations in lime mudstone and calcareous terrigenous mudstone ratios, bedding thickness, and color (Fig. 9A). The section is monotonously very finely textured.

Unit Ma (0–37.5 m) consists of rather poorly exposed, dark brown to brown-gray shaly to platy weathered, clayey

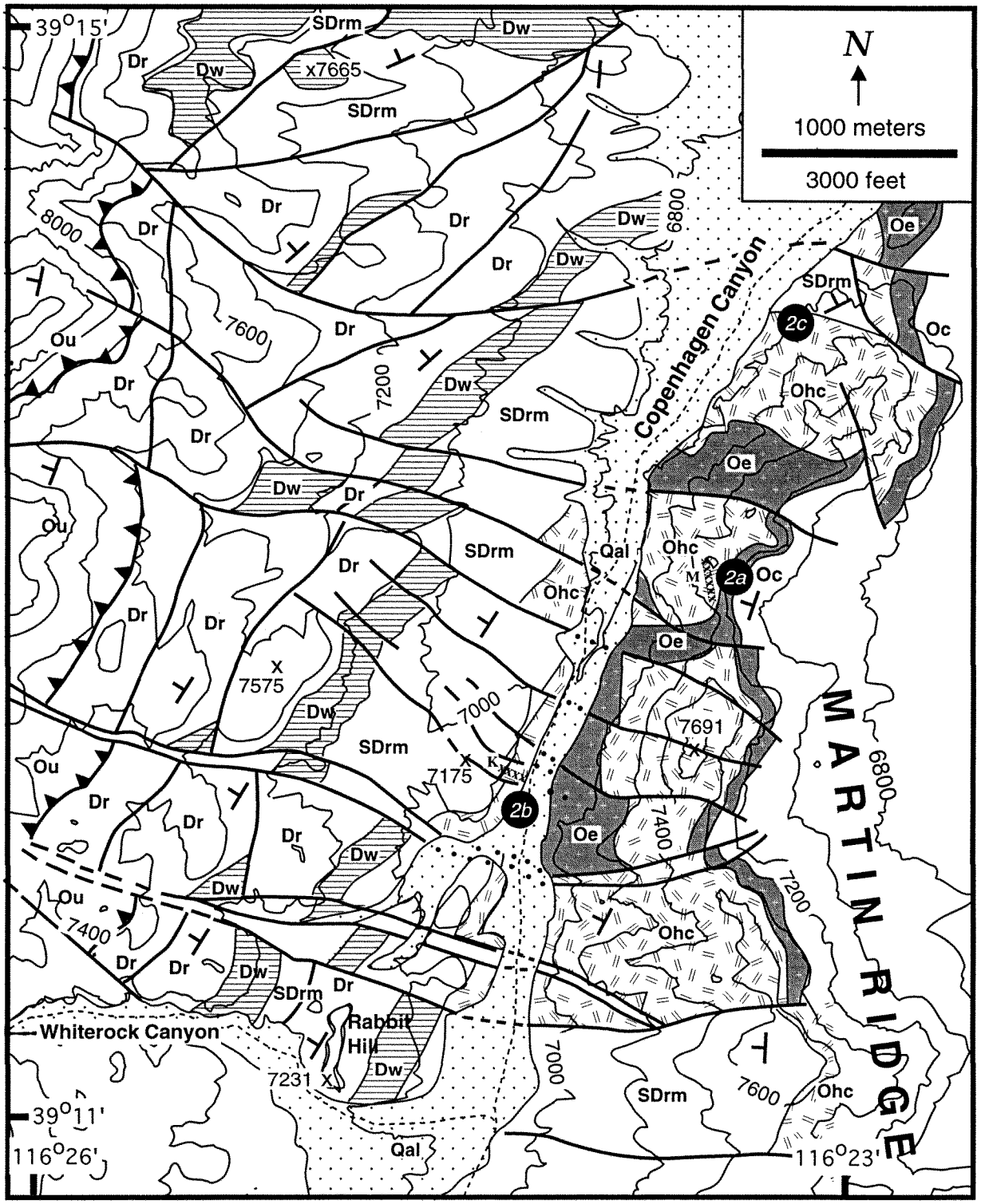

Figure 8. Geologic map of Martin Ridge and Copenhagen Canyon area showing location of ***Field Trip Stops 2a, 2b, and 2c.*** *Location of Martin Ridge (M) and Copenhagen Canyon sections (K) at Stops 2a and 2b are indicated by a row of Xs. The Ordovician to Devonian stratigraphic succession in the map area includes the following: Copenhagen Formation (Oc), Eureka Quartzite (Oe), Hanson Creek Formation (Ohc), Roberts Mountains Formation (SDrm), Windmill Formation (Dw), Rabbit Hill Limestone (Dr). Antelope Valley Limestone (Ou) thrust over Devonian Rabbit Hill Limestone. Modified from Finney et al. (1995a).*

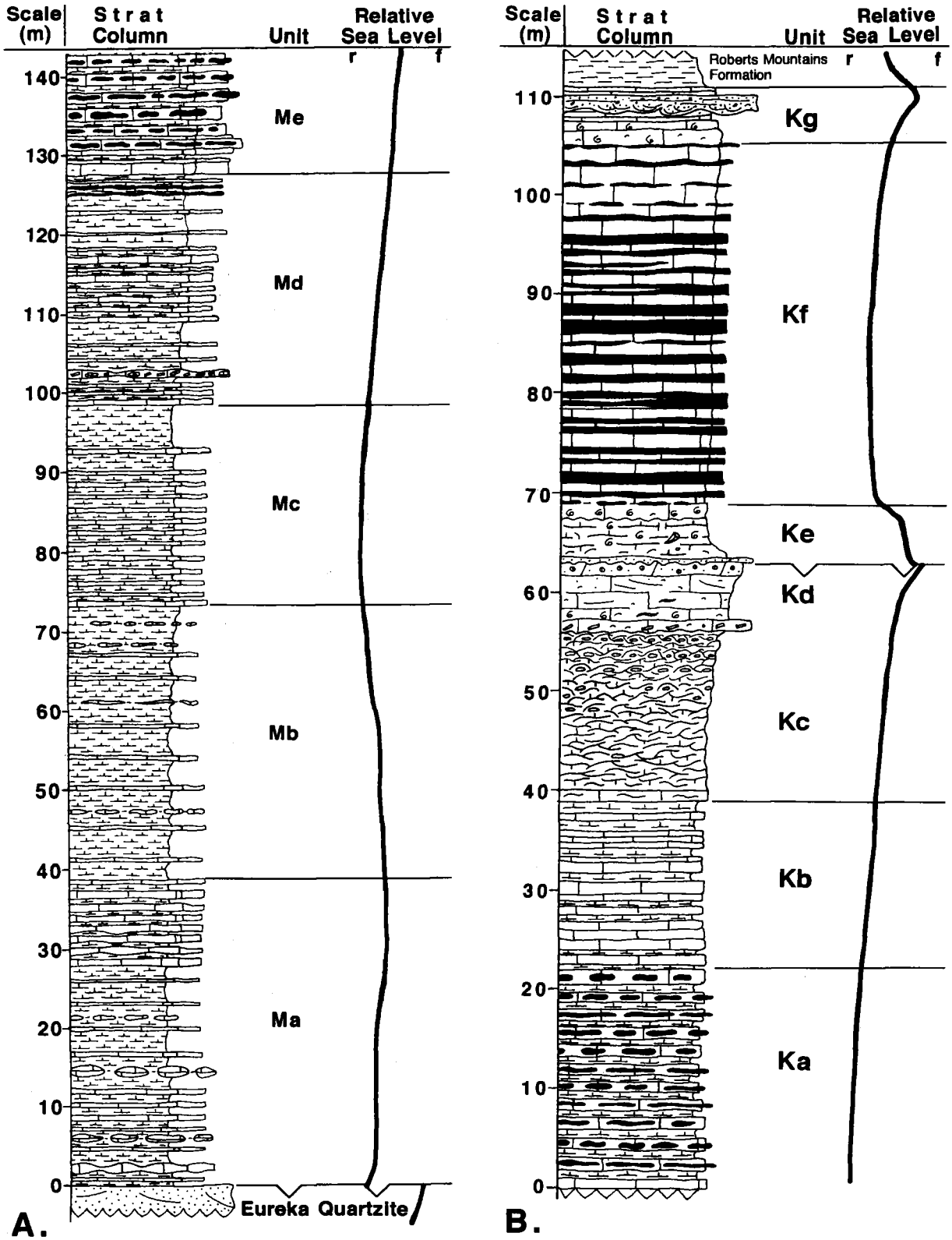

*Figure 9. A. Stratigraphic column and interpreted sea-level curve of lower part of Hanson Creek Formation, Martin Ridge Section (M), **Stop 2a**; B. Stratigraphic column and interpreted sea-level curve of upper part of Hanson Creek Formation, Copenhagen Canyon Section (K), **Stop 2b**.*

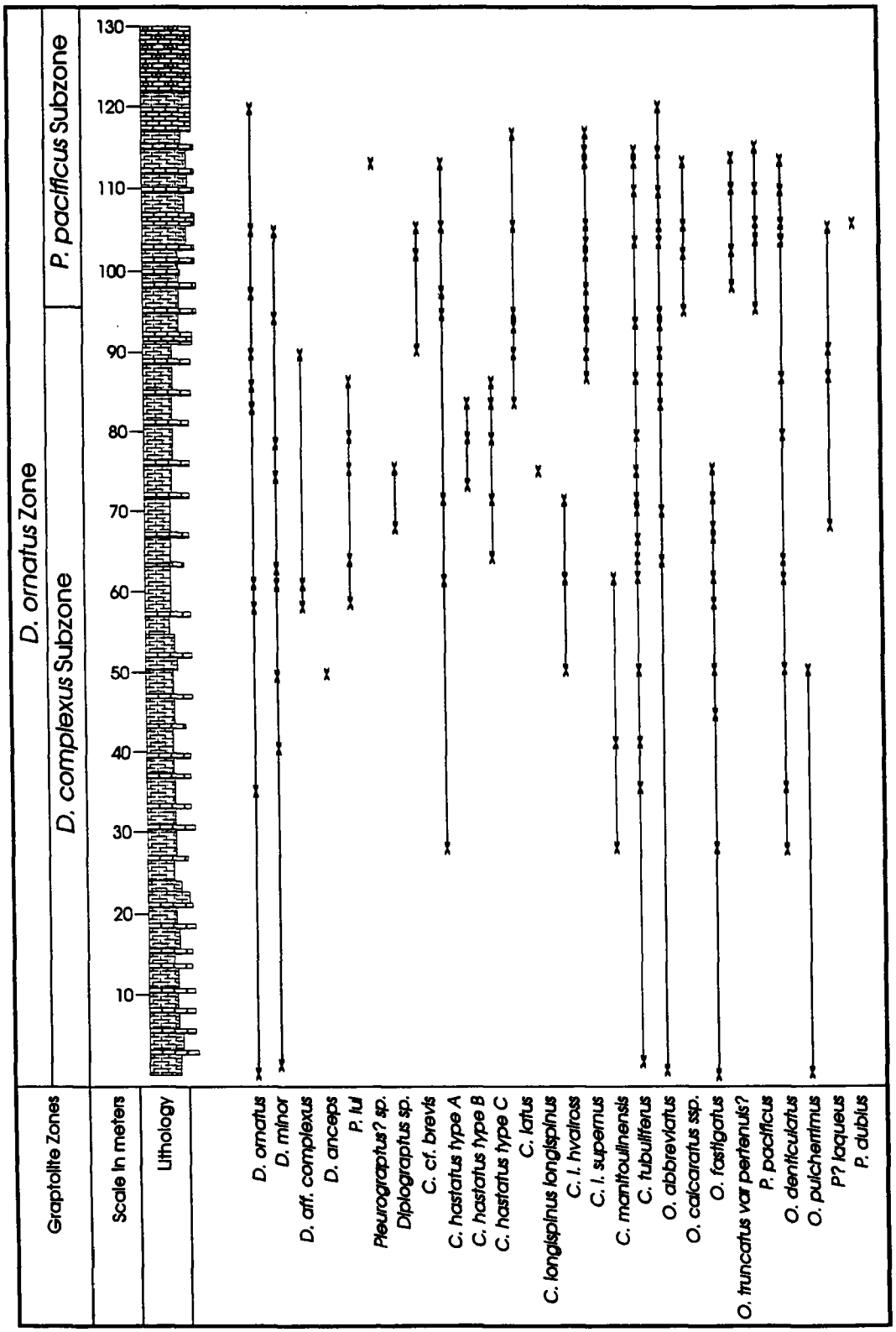

Figure 10. Range chart of graptolites collected by Dworian (1990) from Hanson Creek Formation on Martin Ridge at ***Field Trip Stop 2a****. Stratigraphic levels at which species were collected are indicated by Xs on range bar.*

lime mudstone to calcareous mudstone with interbeds of bench-forming, thicker, dark gray lime mudstone. Much of the platy to very thinly bedded (2–3 cm) clayey lime mudstone is distinctly color laminated. The more resistant, more pure lime mudstone bench/ledge-forming beds are generally 12–15 cm thick, but some are up to 25 cm thick, and commonly show pinch-and-swell and concretionary development (swelling up to 35 cm thick) along strike. These thicker lime mudstone beds commonly show faint to distinct lamination. In the upper part of the unit (25–37.5 m), a tightly clustered succession of 8–22 cm-thick resistant dark gray lime mudstone beds forms a prominent cliff.

Unit Mb is a thick (37.5–73.5 m) succession of the same two lithologies: chippy/platy weathered clayey lime mudstone to calcareous mudstone and thin (3–10 cm) interbeds of more resistant, blocky, dark gray to black, lime mudstone. As in unit Ma below, these rocks are distinctly laminated and emit a fetid odor. The weathered profile is gentle and not punctuated by prominent benches as in Ma, and weathered colors impart a distinct color banding, from pale yellow-gray to gray to medium dark gray to yellow-gray to dark gray.

Unit Mc (73.5–100 m) consists of more rhythmically and distinctly interbedded thin (6–10 cm) dark gray lime mudstone and four 15 cm-thick intervals of brown, shaly weathered clayey lime mudstone to calcareous mudstone. These beds are less distinctly laminated and less fetid than in units Ma and Mb. The upper ~6 m consists of platy to blocky tan gray to pale yellowish gray silty lime mudstone with a single 12 cm-thick resistant dark gray lime mudstone bed.

Unit Md (100–127.5 m) shows a return to more prominent ledge- and bench- to small cliff-forming bedsets of thin to medium bedded, medium to dark gray lime mudstone and thin partings and interbeds of shaly to platy clayey lime mudstone to calcareous mudshale (Fig. 9A). Three bench-forming intervals in unit Md alternate with more recessed intervals, consisting of more poorly exposed, platy to very thin-bedded, medium gray to yellow-tan gray clayey lime mudstone to calcareous mudstone. The uppermost (third) bench contains thicker (up to 35 cm) resistant dark gray lime mudstone beds, some of which have a color-banded weathered appearance with pale tan-gray bases or tops.

Unit Me (127.5–143 m) begins a cliff-forming succession that consists predominantly of medium to thick beds of lime mudstone, with thin gray-brown shaly partings to thin interbeds of calcareous mudstone. About 3 m above the base of the lowest thick (40 cm) lime mudstone bed, the section becomes very cherty. The chert weathers orange-brown and occurs as small blebs, nodules, bulbous and elongate nodules, stringers, and discontinuous wavy layers within limestone beds. The limestones continue to be almost exclusively lime mudstone, with little evidence of allochem content.

Copenhagen Canyon (Section K—**Stop 2b**): Sedimentology

The lower part of the section here (unit Ka) includes lithologies that represent a continuation of unit Me at Martin Ridge (Fig. 9B). The lower cliff-forming succession (0–22.5 m) consists of cherty lime mudstone with shaly partings to very thin interbeds of calcareous mudstone/clayey lime mudstone. Most lime mudstone beds are 10–16 cm thick, are well laminated and emit a fetid odor. Dark gray chert weathers orange-brown and occurs as various sized nodules and thin (up to 12 cm-thick) stringers.

Unit Kb (22.5–39 m) forms a recess between the first and second prominent cliffs. In general the lithologies are similar to KA, but without the chert. Shaly seams and partings are pinkish gray to brownish gray and in places form interbeds up to 2–3 cm thick. In the lower part, silty, fetid lime mudstone beds are thin (7–10 cm), but increase in thickness upsection (8–16 cm thick). These medium to dark gray beds show little discernible lamination.

Unit Kc (39–56 m) begins at the base of a second prominent cliff and the major lithology is dark medium gray lime mudstone, but lighter gray than below and less fetid. Gray-brown shaly partings and seams show an anastomosing relationship with the indistinctly bedded lime mudstone and they also show less reaction with HCl than the shaly partings and seams below. Portions of the lime mudstone appear mottled, but closer examination reveals that this is due mainly to boudin structure, probably related to compaction.

Unit Kd (56–62.7 m) is a thin but heterogeneous succession of facies and becomes more light gray upsection to almost white at the top. The basal bed, about 35 cm thick, has a scoured base and consists of medium to dark brownish gray intraclastic wackestone/packstone with scattered brachiopod fragments. This basal distinct bed is succeeded by about one meter of lighter gray, mottled to blotchy lime mudstone and sparse wackestone. This is succeeded by about 5.5 m of coarsening and thickening upward, poorly bedded, cross-stratified packstone and grainstone. The uppermost meter is partially dolomitized and contains abundant molds of leached ooids and scattered medium to coarse quartz sand (Fig. 9B).

Unit Ke (62.7–69 m) begins with a thin, but variably expressed veneer to thin (up to several cm) bed of well sorted medium quartz sand that in thicker (several cm) development is cross-laminated to wavy ripple-laminated. In a canyon exposure on the west slope of Martin Ridge (**Stop 2c**), this same sandstone is locally up to 15 cm thick

and at all exposures has a sharp but irregular contact with the underlying grainy, dolomitized carbonates. The sandstone layer grades upward into quartz sandy lime wackestone to packstone, succeeded upward by burrow-mottled, medium gray wackestone with scattered partial to whole fossils of brachiopods, pelmatozoans, and corals. Bedding is poorly developed in this fining upward facies. At about 67.5 m there is a pronounced irregular surface that in places looks eroded and scoured. Immediately above are more fossils and rip-up clasts of lime mudstone. From here up to the 69 m level, and the base of unit KF, is a burrow-mottled sparse wackestone with partially dolomitized burrow fillings. The surface at 67.5 m and the one below at 56 m (Kc/Kd contact) are immediately overlain by similar lithologies and show similar irregular, scoured character.

Unit Kf (69–105.25 m) is a rather uniformly homogeneous facies association consisting of alternating beds of dark gray chert and dark gray lime mudstone (to some sparse wackestone). The base of the third and most prominent cliff is at ~85 m in the section. The succession is rhythmic and the chert occurs mostly in stratiform geometries unlike the more nodular and stringer occurrences in unit Ka. Chert beds are dark gray to bluish gray and weather orange-brown to brown-gray. They are 4 to 17 cm thick, but occur mostly in the range of 5–10 cm; some of the thicker beds split into 2–4 thinner beds or seams along the outcrop face.

The lime mudstone beds are dark gray to black and show a return to the dark colors, more distinct laminated structures, and more fetid odors characterizing beds lower in the Hanson Creek. Carbonate beds are mostly 7–12 cm thick, but some are up to 20 cm thick. Some intervals are limestone-dominated; and some are chert-dominated, but the majority of the interval displays even limestone-chert alternations. Above 90 m, there is local disharmonically deformed bedding in a few places. The upper 6.5 m of unit Kf contains much less chert, and in more stringer to nodular occurrences. Limestone beds are thick (20–40 cm) and some are grainy.

Unit Kg is a thin (from 105.25–111 m) heterogeneous succession that begins with a basal thick bed of medium to dark gray skeletal wackestone. This is succeeded by burrow-mottled sparse wackestone, which, in turn, gives way to thinly bedded, dark gray fetid lime mudstone/sparse wackestone. The uppermost meter is developed as a prominent bench that consists of two thick beds of quartz sandy phosphatic lime grainstone. The lower bed is lighter tan gray and has an irregular, in places, deeply scoured base. The scour channels contain nested trough cross bed sets and the main part of the bed is plane-parallel stratified. Concentrations of coarse phosphatized skeletal fragments occur along some of the laminations. The upper bed is darker brown gray and more consistently plane-stratified. Phosphatized peloids and skeletal grains are abundant. This grainy, phosphatic bedset is capped by a thin-bedded dark gray lime mudstone. This is overlain by the shaly, yellowish weathered beds of the Roberts Mountains Formation (Fig. 9B).

Depositional Environments and History: Composite Section

The composite Martin Ridge-Copenhagen Canyon section of the Hanson Creek Formation (Fig. 9A,B) is approximately 250 m thick, and consists mostly, at least in the lower 200 m, of dark gray lime mudstones and calcareous mudstones/clayey lime mudstones that are commonly well laminated, fetid, and lack benthic fauna. These features are consistent with a below storm wave-base, dysaerobic, quiet, relatively deep-water depositional setting. Dunham (1977) and Dunham and Murphy (1976) reported well preserved radiolarians and graptolites from lime mudstone concretions in the lower part of the section. Dworian (1990) recovered abundant graptolites from a number of horizons in the lower 120 m at Martin Ridge. In gross aspects, the lower Hanson Creek has many similarities with the Vinini Creek trench section, viz. dark gray colors, very finely textured sediments, carbonate-siliciclastic rhythms, and lack of bottom fauna, although bundling of beds is different.

A trend toward relative shallowing of the succession is expressed in the greater percentage and thickness of carbonate beds in unit Md, beginning at about 100 m. Our discovery of uncommon specimens of cryptolithid trilobites in a few of these beds is also evidence of shallowing. Relative deepening and shallowing trends are difficult to discern, although unit MC, with thinner and fewer carbonate interbeds and very well-developed internal lamination, might suggest a maximum relative deepening interval. Dunham (1977) surmised that the thicker benches of dark lime mudstone beds signify pulses of carbonate introduced into the environment. This would be consistent with periodic increases in carbonate productivity farther up on the platform, perhaps reflecting subtle shallowing patterns. However, these "pulses" of carbonate deposition could also be an expression of storms or other climatic influences.

Clearly the succession at Copenhagen Canyon sedimentologically shows expression of shallowing. Units Kb and Kc begin to exhibit lighter colors and limestone beds that are more grainy than Ka. Certainly the most notable change occurs in unit Kd, which has a sharp, scoured basal contact and displays a rapid vertical change of facies, including burrowed fabrics, progressively more grainy textures, cross-stratification, and lighter gray colors. This is a classic example of a shoaling upward pattern. Localized

dolomitization and oomoldic porosity in the upper meter of this succession suggest shallowing to shoal conditions, near or at exposure levels, with accompanying vadose diagenesis. The veneer of quartz sand that blankets this surface may reflect shallow transgressive reworking of quartz sand delivered to the outer shelf site during the shallowing (exposure?) phase.

The overlying burrowed wackestone suggests deepening into the subtidal zone below fair-weather wave base. The scoured surface capped with intraclasts at 67.5 m may represent a ravinement surface overlain by a transgressive lag. This may relate to an abrupt change in rate of relative sea-level rise (Fig. 9B). Unit Kf, with the rhythmic interbedding of chert and dark gray lime mudstone, records more abrupt and continued deepening of the environment below storm wave base. Another shallowing trend is indicated at the top of the section with the transition from unit Kf to Kg, with more grainy wackestone textures, burrow mottling, and culminating with the high-energy shoal deposit of cross- and plane-stratified quartz sandy, phosphatic skeletal and peloidal grainstone.

Lone Mountain Section (Section L)—**Field Trip Stop 3**

Overview

The Middle Ordovician to Upper Devonian stratigraphy of the lower plate of the Roberts Mountains thrust is well exposed on the east and south faces of Lone Mountain in an east-dipping homoclinal sequence (Fig. 2). The Hanson Creek Formation is exposed in a continuous section (Section L) low on the west face of Lone Mountain (Fig. 11).

Sedimentology

The section of Hanson Creek Formation at Lone Mountain (Fig. 11) is developed very differently from the sections at Vinini Creek (V) and the Monitor Range (composite M and K) and represents a mid-platform setting that provides an end member context for comparison with the deeper, quieter water sections. The carbonates are entirely dolomite. Dunham and Olsen (1980) discussed the paleogeographic controls on early, shallow-burial, mixed-water dolomitization for this mid platform setting. This section also contains a thinner succession and more heterogeneous facies association, all consistent with the mid-platform position.

The section, as described by Ross (1970), Dunham (1977), Dunham and Olsen (1980), and Droser and Sheehan (1995), begins above the sharp contact with the Eureka Quartzite, with the basal few meters consisting of dolomitized pelmatozoan grainstone (La), containing quartz sand reworked from the underlying burrow-mottled Eureka. By 10 m above the base, dolomitized coral and stromatoporoid colonies are preserved in growth position, encased in bioclastic dolowackestone and packstone (Lb). At about 20 m is a transition to pelmatozoan dolograinstone, which occurs in thick, cross-stratified beds (Lc).

At about 38 m into the section, these grainstones are overlain by medium gray dolomudstone/wackestone or floatstone beds, mottled with distinct burrow structures and containing scattered brachiopods and small rugose corals (Ld). Droser and Sheehan (1995) also report bryozoans and rare trilobites, as well as brachiopods with "snowshoe" morphologies, adaptations for life on soft substrates. At 65 m above the base of the section, red-orange intraclasts of irregularly laminated dolomite are scattered in a matrix of gray-brown dolomudstone. The upper contact with this 1 m-thick intraclastic layer contains fissures up to several centimeters deep that are filled with dark red or red-orange dolomite mud and silt with scattered quartz grains (Fig. 11).

A one meter-thick red-orange quartz sandy dolostone overlies the fissured surface and is capped by a 1–2 m-thick laminated dolomite crust. At 67 m this red interval is overlain by about 3–4 m of cross-stratified, well-sorted, quartz sand-carbonate pellet dolograinstone (Le). This, as well as the sandy interval at the base of unit Ke in the Copenhagen Canyon section, represents the "sandy zone," originally described from seven sections in Nevada by Mullens and Poole (1972), including, significantly, the Copenhagen Canyon section.

The quartz sandy interval is overlain by about 5–6 m of bioclastic dolowackestone to skeletal dolomudstone, containing a low-diversity fauna of brachiopods and ostracodes (Lf). From about 76–82 m, the succession contains dark dolomudstone and irregularly laminated light-dark dolomudstone bands with LLH-stromatolites, channel fills, fenestral fabrics, and sheet and prism cracks (Lg). This is succeeded by about 8 m of lighter gray, burrow-mottled dolopackstone. At 90 m, there is an abrupt change to medium gray dolostone with abundant chert nodules and stringers and discontinuous beds (Lh). The dolostones include grainy textures as well as irregular laminations and low-relief LLH-stromatolites. Dunham and Olsen (1980) reported well-preserved acritarchs within the chert, suggesting that chertification had preceded dolomitization of the associated carbonate.

Depositional Environments and History

The Lone Mountain section shows clear evidence of shallower water deposition than at Martin Ridge-Copenhagen Canyon. Thicker beds, lighter colors, more grainy textures, more benthic faunas, microbial structures, and pervasive dolomitization are consistent with a shallow, well-oxygenated, mid-platform setting. Dunham (1977) and Dunham and Olsen (1980) interpreted the basal quartz

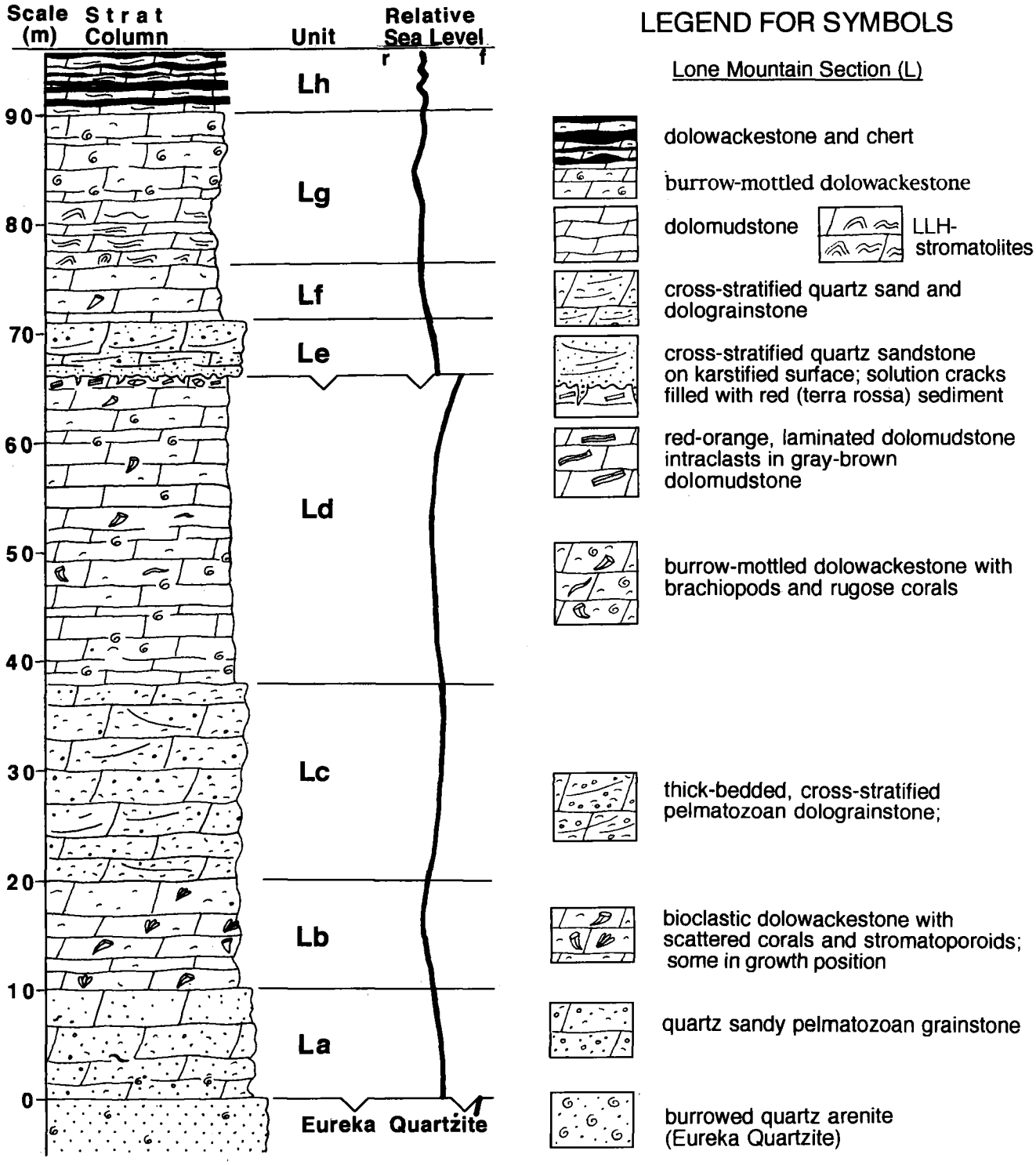

Figure 11. Stratigraphic column and interpreted sea-level curve of Hanson Creek Formation at Lone Mountain (L), Stop 3. Modified from Dunham (1977) and Droser and Sheehan (1995).

sandy pelmatozoan dolograinstone as the deposit of a high-energy strand or shallow subtidal shoal. They regarded the Hanson Creek-Eureka contact as cartographically sharp but depositionally gradational, and the change from quartz sand to carbonate sediment to reflect not a change in depositional environment, but rather a change in the nature of sediment supplied to the environment. This is in marked contrast to the section at Martin Ridge where shallow-marine high-energy quartz sands of the uppermost Eureka are abruptly overlain by deep-water lime mudstones of the basal Hanson Creek Formation.

The overlying fossiliferous packstones with diverse fauna indicate well-oxygenated waters of normal marine salinity on an open-marine, storm-influenced shelf. The pelmatozoan grainstone facies that begins at about the 20 m level is interpreted as representing the encroachment of laterally migrating skeletal sand shoals into the area (Dunham, 1977). The transition from grainstone to burrow-mottled and fossiliferous muddy textures is interpreted to represent the continued migration of these skeletal shoals in a basinward direction and the establishment of a quiet-water, restricted shelf lagoon in the lee of the shoal complex. The uppermost meter of the brown dolomudstone facies contains reddish intraclasts, most likely thoroughly oxidized in an emergent condition.

The red-colored interval from 66–67 m suggests a terra rossa condition and paleosol formation. The underlying red dolomitic silt and quartz sand-filled fissures fit the description of solution grikes, a common surface and shallow subsurface karst feature, indicative of subaerial exposure (Esteban and Klappa, 1983). The overlying quartz sandy interval likely represents shallow transgressive reworking of sands spread across the exposed platform site during sea-level lowstand and emergence.

The bioclastic dolowackestone and dolomudstone, containing the restricted fauna of brachiopods and ostracodes, represents the return to restricted lagoonal conditions. The overlying facies with LLH-stromatolites, crinkly microbial laminites, light-dark banded dolomudstones, prism cracks, sheet cracks, tepees, and enlarged fenestrae are consistent with a peritidal depositional system. At the top, facies of burrow-mottled skeletal dolopackstone, becoming cherty at about 90 m, suggests a gradual deepening to more subtidal depths.

SYNOPSIS OF PALEOENVIRONMENTS/ PALEOGEOGRAPHY/RELATIVE SEA-LEVEL CHANGES

Dunham (1977) interpreted the Martin Ridge Hanson Creek section as deposits of an intrashelf basin on the outer part of the platform. In fact, he called this the Martin Ridge Basin whose location and rough dimensions he constrained by the character of three stratigraphic sections, with the Martin Ridge section in the middle (Dunham, 1977, p. 163, fig. 6). Local subsidence and rapid drowning followed deposition of the shallow-marine Eureka Quartzite. Later, near the end of the Ordovician, the Martin Ridge Basin shoaled to shallow depths (or even emergence?), as suggested by the shallow-water carbonates and overlying quartz sandy zone. Dunham interpreted the Martin Ridge depression as an intraplatform sub-basin that was not extremely deep (~100 m at the most), but more likely restricted in its circulation, thus mimicking deeper water conditions. He envisioned the sub-basinal depression as a sink for the accumulation of lime mud, which eventually nearly filled it by the end of the Ordovician, as suggested by the upsection increase in lime mudstone deposition and the shoaling to high-energy conditions. The basin probably was isolated initially from areas of high carbonate productivity. Increased input of lime mud up section probably reflects encroachment of areas of high carbonate mud productivity at the margins of the intraplatform basin. Eventually, bioclastic material and whole shells of diverse fauna were contributed to the rapidly accumulating lime muds. According to Dunham (1977, p. 162), "The sorted quartz sand and oolitic deposit of Mullens and Poole (1972), present within fossiliferous packstones and wackestones at the top of the section, attests to shallow-water conditions and the final filling of the Martin Ridge depression, from a maximum depth of little more than 100 m to a final depth of a few tens of meters at the most."

Dunham placed the Hanson Creek Formation at the Lone Mountain section, at this time of Martin Ridge Basin "filling," at the transition between shallow, open-marine shelf, skeletal sand shoals, and a back-shoal lagoon, all with a NW-SE (present coordinates) orientation. When the Martin Ridge Basin shoaled, the Lone Mountain area had shallowed to a tidal flat complex (Dunham, 1977, p. 163, fig. 7). Interestingly, Dunham (1977) attributed the exposure surface and sand deposition in the Lone Mountain section to tidal flat development and shallowing to sea level by supratidal emergence—an autocyclic expression. Dunham (1977) stated that shoaling at the top (remember, Dunham followed convention and placed the chert-rich part of the section in the overlying Roberts Mountains Formation) of each section is the single most striking feature of Hanson Creek deposition; yet he did not put this into the context of a major sea-level drawdown event that produced a basin-wide disconformity! This pronounced shallowing and emergence, particularly in the Martin Ridge depression, together with the timing as evidenced by biostratigraphy, would seem to be the "smoking gun" for sea-level drawdown related to Hirnantian glaciation in the latest Ordovician.

At Lone Mountain, the karstified surface and paleosol at 65–66m is a sequence boundary, separating overlying retrogradational (backstepping) deposits from underlying progradational (forestepping) deposits (Fig. 11). At Martin Ridge–Copenhagen Canyon, the corroded surface overlain by the quartz sandy layer is an extension of this same sequence boundary, or, at least, its correlative conformity. A combination of basin-filling by lime mud and sea-level drawdown could well have exposed this outer, embayed part of the platform.

Regional paleotectonic and paleogeographic relationships suggest the allochthonous Vinini Creek Section represents an off-platform slope or basin depositional setting, perhaps far removed from the platform. Certainly there is no clear-cut signal for bathymetric change near the Ordovician-Silurian boundary as in the other two sections. Perhaps abruptly increasing lime mudstone-shale ratios near the top of the section (unit VAg) reflect basin shallowing. The abundance of phosphatic grains in the grainy layers throughout the section suggests upwelling and phosphatization up-slope, likely near the platform margin. One scenario sees the carbonate-poor, organic-rich unit VAe as exemplary of the burial ground for massive amounts of organic carbon. Arguably this is a signature of the condition that lowered pCO_2 below the critical threshold to trigger Gondwanan glaciation (model of Kump et al., 1995). Massive burial of organic carbon could have reinforced and climaxed a continued pCO_2 drawdown due to global decrease in volcanic activity (source) and increase in continental silicate weathering (sink) related to Middle to Late Ordovician orogeny (such as the Taconic-Famatinian; Dalziel, 1997).

The thin but distinctive unit VAf, with its decreased graptolite diversity might represent the onset of Gondwanan (Hirnantian) glaciation. Unit VAg, the return to carbonate deposition, perhaps reflects restoration of the carbonate factory on the shelf related to lowering of sea-level (to level conducive to carbonate production) accompanying glaciation. The presence of *N. persculptus* zone graptolites at about the 2.2 m level of Unit VCh corresponds chronostratigraphically to the fossiliferous wackestone (unit Ke) at Copenhagen Canyon, suggesting perhaps the early phase of post-glacial sea-level rise and recovery. A *persculptus* fauna occurrence one meter higher corresponds to the basal part of the rhythmic lime mudstone-chert bed succession (unit Kf) at Copenhagen Canyon, suggesting the early phase of post-glacial sea-level rise and recovery. A major disconformity occurs at the VCh/VCi contact where shale with middle Llandovery graptolites and interbedded chert rests sharply on *N. persculptus* Zone uppermost Ordovician carbonate beds. This hiatus at the Ordovician-Silurian boundary in the Vinini Creek section is partially filled by the upper two-thirds of the rhythmic limestone-chert section (unit Kf) at Copenhagen Canyon, reflecting much more continuous and active sedimentation on the outer platform during post-glacial sea-level rise, with attendant sediment starvation in the deep-water Vinini basin.

GRAPTOLITE EXTINCTION AND RECOVERY

Graptolites are the only visible fauna from which to examine the Late Ordovician extinction in the central Nevada sections. They are abundant throughout the Vinini Creek section and the upper part of the Martin Ridge section; they are scarce in the Copenhagen Canyon section, and absent at Lone Mountain.

Graptolites flourished on continental margins (Finney and Berry, 1996; Berry and Finney, 1996), and during deposition of beds in the *D. ornatus* Zone they were prolific in waters above the outer platform (Martin Ridge section) and the lower slope to basin (Vinini Creek section). Preliminary biostratigraphic correlations suggest that with the initiation of a sea level fall, graptolites disappeared from waters over the outer platform (Martin Ridge section) during deposition of beds correlative with the middle *P. pacificus* Subzone. Their local extinction was rapid and corresponded to the facies change reflected in the appearance of thin to thick-bedded lime mudstones. Yet graptolites flourished in waters over the lower slope to basin, and their remains contributed greatly to the organic-rich unit VAe.

Graptolite abundance decreases rapidly from the upper part of the organic-rich unit to the brown interval VAf. This corresponds to the boundary between the *P. pacificus* Subzone with its diverse, globally widespread fauna, and the *C. extraordinarius* Zone with an impoverished fauna of three to five species that are survivors of the late Ordovician extinction. The Vinini Creek section preserves a fairly continuous record of the extinction. It is gradual, occurring from approximately 16 m to 19 m with species terminating one after the other. Although diversity decreases substantially, abundance remains high to the top of VAf, where medium to thick lime-mudstone beds of VAg dominate. These carbonate beds, which also extend up to approximately 2 m into unit VCh, appear to correlate with the sequence boundary in the Copenhagen Canyon and Lone Mountain sections. They represent the record of the Hirnantian lowstand in the basin facies; the graptolite fauna is reduced to three species, and specimens are common to rare. The upper 2 m of carbonate beds in VCh record an increase in species diversity with the appearance of the *N. persculptus* fauna. This correlates with the post-glacial sea-level rise that quickly led to sediment starvation in the deep-water Vinini basin. The stratigraphic

record of graptolites in the basin facies is broken at the Ordovician-Silurian hiatus. It is not reestablished until the middle Llandovery. Sediment accumulation continued on the platform through the early and middle Llandovery, but graptolite populations did not develop extensively in the overlying waters until the late Llandovery.

ROAD LOG

Day One: Salt Lake City to Carlin to Vinini Creek section (**Stop 1**) in Roberts Mountains to Eureka (October 16, 1997)

From Salt Lake City, travel west on Interstate Highway 80 to Carlin, Nevada, a distance of 254 miles. At Carlin, exit I-80 at Nevada Highway 278 and travel south towards the Roberts Mountains (Fig. 2). In the first ten miles, we cross the Humboldt River and climb over a low summit of late Tertiary volcanic rocks before driving down into the north end of Pine Valley. Pine Valley opens to the south and is bounded by the Piñon Range to the east and the Cortez Range to the west. The Piñon Range is composed largely of Mississippian-Pennsylvanian Chainman Shale and Diamond Peak Formation, which are detrital sediments eroded from the Antler orogenic belt and deposited on the western margin of the adjacent foreland basin (Smith and Ketner, 1975). Pine Mountain, an 8285 foot (2650 m) peak that stands out at the front of the range, is composed of Devonian carbonates that are considered allochthonous and to have been emplaced above the younger foreland basin sediments during Mesozoic thrusting (Ketner and Smith, 1974). The northern Cortez Range consists largely of Jurassic granitic rocks and volcanics. Small oil fields, probably sourced from Chainman Shale, are immediately west of Highway 278 at Tomera Ranch and Willow Creek, approximately 10 and 20 miles south of Carlin. The much larger Blackburn field is to the west of the highway at 30 miles south of Carlin (Montgomery, 1988). To the east beyond the oil field is Mineral Hill at the northern end of the Sulphur Springs Range, which is composed largely of Silurian and Devonian carbonate rocks of the autochthonous eastern facies and Ordovician to Devonian detrital rocks western facies rocks in the upper plate of the Roberts Mountains thrust. These are the easternmost outcrops of rocks of the RMA at this latitude.

Approximately 30 miles south of Carlin, the Roberts Mountains are clearly visible to the south and west of Highway 278; farther to the west are the northern Simpson Park Range and behind it the southern Cortez Range. The high ridges and peaks of the Roberts Mountains are composed of Ordovician to Devonian limestone and dolomite and the upper Ordovician Eureka Quartzite. Rocks of the Roberts Mountains allochthon crop out over large areas of lower slopes on the east and west sides of the range. Follow Highway 278 south into Garden Valley and along the east side of the Roberts Mountains.

Approximately 65 miles south of Carlin turn right (west) onto dirt road, **reset the odometer to zero**, proceed 0.1 mile, and then take right fork in road that leads up Vinini Creek. At mile 1.8, the road crosses to north side of Vinini Creek. At mile 4.1, the canyon widens. The type area of the Vinini Formation is the south-facing slopes above Vinini Creek. Bedding dips to the east. Down section is to the west. At mile 4.3, we reach **Stop 1**.

STOP 1—Vinini Creek (Figs. 5–7)—basinal setting

Here we will examine the trench exposure in the uppermost Vinini Formation. Features to note and consider include:

1. bundling of lime mudstone and shale/mudstone beds;
   How might this relate to paleoceanographic/paleoclimatic and relative sea-level changes?
   What is the influence of diagenesis on the bedding?
   Why does the uppermost Vinini contain abundant limestone and very little chert in contrast to siliciclastic-chert association in subjacent part and how might this relate to greenhouse-icehouse transition?
2. thin grainstone laminae/beds;
   How did they form and what is their significance?
3. unit VAe, the organic-rich succession;
   Why is this interval more organic rich than others and how might it relate to paleoceanographic/paleoclimatic conditions?
4. extinction events;
   What model best explains the extinction patterns observed?
5. sharp unconformity at Ordovician-Silurian boundary;
   What is its significance?

Leave the direction we came, traveling east 4.6 miles back down Vinini Creek to Highway 278; turn right (south) to Eureka. **Reset odometer to zero.** Garden Pass is at mile 2.0. Gravel pits immediately left (east) of the road are dug into graptolite-rich black shales of lower part of upper member of Vinini Formation. Graptolites collected in this area by Walcott were reported by Gurley (1896) and used by Merriam and Anderson (1942) to date the Vinini Formation. The Pony Express Trail sign is at mile 6.2. The highway curves east, and at mile 8.6 it passes through hogback ridges held up by Pennsylvanian to Permian Garden Valley Formation. It then curves to south down Diamond Valley to U.S. Highway 50 at mile 25. Turn left (east) and enter Eureka at mile 27.5.

Day Two: Eureka to Monitor Range (**STOPS 2a, 2b, & 2c**) and back to Eureka (October 17, 1997)

Drive west from Eureka on U.S. Highway 50 (Fig. 2), cross Diamond Valley and at mile 6 pass through Devils Gate, where Upper Devonian Devils Gate Limestone dips steeply eastward and is overlain by the Pilot Shale. The broad valley extending westward and southward beyond Devils Gate is Antelope Valley. Just north of the highway and in the middle of Antelope Valley is Lone Mountain that is visited at **Stop 3**; the Roberts Mountains are farther to the north.

Past Lone Mountain is the north end of the Monitor Range, which occupies the west side of Antelope Valley. Leave Highway 50 at mile 17.4 and turn south down a dirt road that extends parallel to the mountain front. The Antelope Range, the eastern limit of the valley, is to the south and east; the Antelope and Monitor ranges merge at the south end of the valley.

The road southward forks at mile 22; the right fork passes westward around the north end of Martin Ridge and then turns southward down Copenhagen Canyon. In Copenhagen canyon, rocks to the east of the road include the Eureka Quartzite, Hanson Creek Formation, and Roberts Mountains Formation repeated in many transverse fault-bounded blocks that comprise the northern part of Martin Ridge. West of the road are cliffs of uppermost Hanson Creek Formation overlain by shale of the Roberts Mountains Formation (Fig. 8). At mile 25 we stop to climb up Martin Ridge to the east to reach **Stop 2a**.

STOP 2a—Martin Ridge (M), Monitor Range (Figs. 8, 9A, &10)—Outer platform setting

At this stop we will traverse the crest of Martin Ridge and examine the lower 140+ m of the Hanson Creek Formation. The topographic expression of the Hanson Creek Formation is distinctive. The lower 50 meters form a gentle slope; the slope steepens appreciably at 60 to 70 m; medium to thick bedded lime mudstones above 120 m form a cliff. Features to note and consider include:

1. Eureka Quartzite-Hanson Creek contact (compare with what we will see at Stop 3, Lone Mountain, Fig. 11);
   Is this an unconformity?
2. character of lime mudstone benches in unit Ma;
   What do the lime mudstone buildups suggest about relative water depth?
3. character of unit Mb;
   Is this interval an expression of relative deepening?
4. bundling of lime mudstone and shale beds in unit Md;
   Does this represent a relative shallowing trend?
5. odd breccia lens at ~102 m (unit Md);
   How did it form?
6. chert nodules and stringers in unit Me;
   What is the significance of the chert?

From Martin Ridge, we can see the location of the Copenhagen Canyon section (Section K) on the low ridge immediately east of the Copenhagen Canyon road (Fig. 8). The east face of this ridge is marked by three levels of cliff-forming limestone. The lowest is unit Ka, which overlaps stratigraphically with Me (Fig. 9A, B). The middle cliff is held up by units Kc and Kd. The highest level of cliffs in unit Kf. Upon leaving Martin Ridge, return to the vehicle and drive south 0. 5 mile, parking at the base of Section K, which is **Stop 2b**.

STOP 2b—West side of Copenhagen Canyon (K), Monitor Range (Figs. 8, 9B)

Outer platform setting

At this stop we will continue through the upper half of the Hanson Creek Formation. The basal exposures here are probably within a few meters (+/–) of the top of the M section (Stop 2a). Features to note and consider include:

1. unit Ka;
   Do you observe any evidence of bioturbation in this succession?
2. unit Kb;
   Why does the chert disappear?
3. anastomosing structure in unit Kc;
   Is this related to compaction or bioturbation?
4. unit Kd—basal contact, colors, bedding, fauna
   Is this evidence of a shallowing-upward pattern?
   What is its significance?
5. unit Ke—basal contact, thin quartz sand zone, overlying sparsely fossiliferous wackestone;
   What is the significance of the quartz sand?
   Do you see any evidence of exposure on the underlying surface?
6. interbedded chert and lime mudstone of unit Kf;
   Why the more interbedded character versus nodular chert of units Ka and Me?
   **This interval fills the hiatus of the Ordovician-Silurian unconformity at the Vinini Creek section.
7. facies variability in unit Kg, with special focus on the cross-bedded, phosphatic quartz sandy grainstone.
   Is the base of the grainstone an unconformity?

Leave Section K driving 1.5 miles north, back up the Copenhagen Canyon road. Stop, hike up a canyon in the west side of Martin Ridge. This is **Stop 2c**

STOP 2c—canyon in west side of Martin Ridge.

This is a short stop to examine good exposures of the transition from units Kd to Ke, with special focus on development of the sandy zone.

1. Compare this exposure with the Kd/Ke interval at

the previous stop (Stop 2b), especially the Kd/Ke contact and the overlying sandy zone.
Does this better exposure shed any more light on the significance of the transition?

Return to vehicle and drive back to Eureka.

Day Three: Eureka to Lone Mountain (**Stop 3**) to Salt Lake City (October 18, 1997)

Drive west out of Eureka on Highway 50 to Lone Mountain (Fig. 2). Just before a small bridge that is 0.6 miles west of Eureka County milepost 19, turn right onto dirt trail. **Reset odometer to zero**. Drive north towards Lone Mountain. The eastward dipping rocks of Lone Mountain range from Antelope Valley Limestone to the west through Eureka Quartzite (white band beneath dark beds), Hanson Creek Dolomite and a thick Silurian and Devonian sequence with Devils Gate Limestone at the top to the east.

At the junction at mile 2.7, turn left (west) and drive to the next fork in the road at mile 3.6. Take the left fork. At mile 3.8, take a right fork; at mile 4.0 take a left fork and after 0.3 mile park beside an old charcoal oven site. This is **Stop 3**.

STOP 3—Lone Mountain (L; Fig. 11)—mid-platform setting

At this stop we have the opportunity to examine a mid-platform expression of the Hanson Creek Formation. This provides an end member comparison with the highly condensed basinal section at Vinini Creek and the thick, outer platform sub-basin section at the Monitor Range. Features to note and consider include:

1. thickness difference between this and the Monitor Range Hanson Creek section;
   What were the main controls on this difference?
2. Eureka-Hanson Creek contact;
   How does it compare with the section at Martin Ridge?
3. facies types and succession in comparison with Monitor Range section;
   How do you explain the difference from an accommodation perspective?
   Why is this section dolomite?
4. unit Ld/Le transition;
   What does this transition express?
   Is the red zone a paleosol?
   Is the underlying surface the expression of sea-level drawdown related to Hirnantian glaciation?

From the Lone Mountain section, return to Eureka and then continue west on Highway 50 for 77 miles to Ely, Nevada. Along the way, we cross the Diamond Range, the northern end of the Pancake Range, the White Pine Range, and, at Ely, the Egan Range. From Ely, travel 118 miles north on Alternate U.S. Highway 93 to Wendover, Utah. There we join I-80 and drive eastward 117 miles to Salt Lake City.

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