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# GEOLOGY

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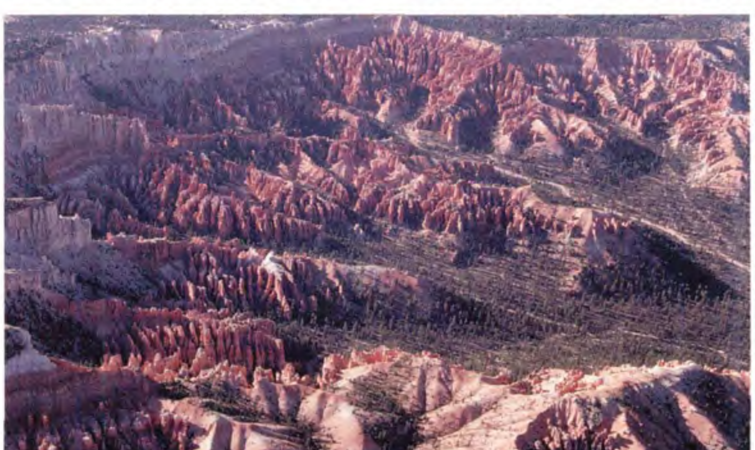

PART 1 ONE

EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

VOLUME 42 • 1997

# 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 Devonian Alamo Impact Event, Global Kellwasser Events, and Major Eustatic Events, Eastern Great Basin, Nevada and Utah

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ABSTRACT

Twenty latest Middle Devonian to earliest Mississippian, mainly Late Devonian, events are recognized in eastern Nevada and western Utah. These are sequentially numbered and dated by a recent biochronologic time scale, based on conodonts but tied to a new radiometric date of 354 Ma at the Devonian-Mississippian boundary. The most significant, recent addition to the listing of recognized events is Event 6, the Alamo Impact Event, dated as early Frasnian *punctata* Zone at ~367.2 Ma. This event is based on the Alamo Breccia, which occurs mainly in Lincoln County, Nevada, and is herein formally named as a member in the lower parts of the Guilmette Formation and Devils Gate Limestone. The huge megabreccia, detached slide blocks, tsunami-related debris flow and turbidites, ejecta, and injected dikes, sills, and slabs, associated with this event, are demonstrable at four accessible outcrops, viewable during a formal or self-conducted field trip of two day's duration, north and west of the town of Alamo, Nevada.

A significant eustatic deepening event, Event 8, dated as late Frasnian Early *rhenana* Zone at ~365.5 Ma, produced a submarine discontinuity in deep-water settings, areally extended the intrashelf Pilot basin, and drowned organic buildups in shallower water. The position of this event is observable in an additional two days at four accessible outcrops at the south end of the Hot Creek Range and at Devils Gate in Nevada, and in the Confusion Range in western Utah. The position of the Upper Kellwasser Event, Event 10, redated at ~364.1 Ma, which produced the global late Frasnian mass extinction, is observable at the same four outcrops. Evidence for a tsunamite, associated with this global event, is present at Devils Gate, and turbidites, only 15 cm apart, bracketing its position within a turbiditic sequence, are viewable at Coyote Knolls, Utah.

Most of the other eustatic events or major regional sea-level changes are to be viewed during the same four days. A new formation, herein named the Middle Devonian Fox Mountain Formation, is present at or near three of the eight localities. The Fox Mountain, which intervenes between the Guilmette Formation and Simonson Dolostone, underlies a large area of eastern Nevada and western Utah. Its western equivalent can be recognized near Eureka, Nevada, in the upper Bay State Dolostone, underlying the Devils Gate Limestone.

## INTRODUCTION

The Late Devonian was a time of great changes in global tectonics, climate, and biota. This upheaval followed a long episode of tectonic quiescence and biotic endemism during the Early Devonian and early Middle Devonian. A series of well-dated Late Devonian catastrophic and abrupt eustatic events occurred during a general early Late Devonian (Frasnian) transgression, which had begun in the late Middle Devonian (Givetian), and continued through the ensuing general late Late Devonian (Famennian) regression. The triggering mechanisms for this great Late Devonian upheaval was probably an episodic series of impacts by chains of comet showers. The greatest biotic change was the late Frasnian global mass extinction that occurred in connection with the Upper Kellwasser Event. The final extinction at the Frasnian-Famennian boundary was probably immediately preceded by increased cosmic radiation that is suspected to have helped produce bizarre genetic changes in some conodont species. The ensuing general Famennian regression was interrupted by a series of moderate transgressions that are interpreted to have resulted from melting of ice during interglacial stages of Southern Hemisphere glaciation.

Less well known than the global Upper Kellwasser Event is the Alamo Event, which has only recently been documented to have resulted from an offshore marine impact and ensuing supertsunamis (Warme and Sandberg, 1995, 1996; Kuehner, 1997). Evidence for this impact, in the form of megabreccias, shocked quartz grains, an iridium anomaly, lapilli-like ejecta, and stranded high-water deposits, extends at least 190 km from north to south in southern Nevada. The shocked quartz grains occur not only within the upper, turbiditic part of the megabreccia, but also within dikes and sills injected into Middle Devonian rocks far below the breccia close to the impact site. New discoveries suggest that the effects may have been even more extensive.

### Scope and Route of Field Trip

The mountain ranges of eastern Nevada and western Utah, because of excellent exposures and sparse vegetation, provide an unparalleled opportunity to examine the evidence for Late Devonian catastrophic events as well as for major eustatic rises and falls. This field trip from Las Vegas to Salt Lake City (Fig. 1), in association with the 1997 annual meeting of the Geological Society of America, is intended to provide a brief, four-day overview of spectacular Late Devonian events in a transect from shallow-water carbonate platform to deep basin.

Paleotectonically, the area traversed is mainly the vast, shallow-marine Late Devonian carbonate platform represented largely by the Guilmette Formation, which encloses the deeper Pilot basin, an intraplatform basin separated from the proto-Pacific Ocean to the west by initial growth of the Antler orogenic welt (Sandberg et al., 1989, fig. 12). Some of the western outcrops to be studied are formed by the Devils Gate Limestone. Its lower member was deposited as part of the carbonate platform, but its upper member was deposited mainly as turbidites and debris flows on a west-dipping foreslope, or, in areas to the north, on an east-dipping slope bordering the Pilot basin. One more westerly locality to be visited displays the Woodruff Formation, composed of transitional-facies cherts and siltstones deposited at the toe of the slope, west of the welt.

North of the town of Alamo in southern Nevada (Fig. 1), Stops 1 to 4, to be visited during the first two days of the field trip, are devoted to the Alamo Breccia, which was deposited mainly on the carbonate platform. Stop 4, however, lies off the platform on the foreslope to the west, and will be visited to observe dikes, sills, and quartz sandstone (now quartzite) slabs that were injected into Middle Devonian rocks below the Alamo Breccia.

As most known outcrops of the Alamo Breccia lie within Lincoln County, a generalized geologic map of that area (Tschanz and Pampeyan, 1970) serves as a useful guide. Later studies, however, have shown that locally some Devonian formations were misidentified.

Farther north and west in Nevada, Stops 5 and 6 (Fig. 1), to be visited on the third day of the field trip, feature outcrops of Woodruff Formation and Devils Gate Limestone, respectively. Useful, up-to-date geologic maps are as yet unavailable for these localities. In western Utah, Stops 7 and 8, to be visited on the fourth day, are located in the Tule Valley and in the Confusion Range to the west, respectively. These stops show the turbiditic and debris-flow slope deposits on the eastern side of the Pilot basin. Excellent, detailed geologic maps (Hose, 1963; Hintze, 1974 ) are available for these stops.

### Sources of Data

For a general overview of the Devonian of the Western United States, a paper by Johnson et al. (1991) serves as a useful introduction. However, for a better understanding of the setting and sedimentation of Upper Devonian rocks of the region, detailed papers by Sandberg and Poole (1977) and Sandberg et al. (1989) are recommended. The latter paper contains an extensive bibliography. Underlying Middle Devonian rocks, which display the oldest four events, are covered in moderate detail by Johnson and Sandberg (1989). Criteria for distinguishing global Devonian eustatic events from local or regional sea-level changes induced by tectonic events, such as the Antler orogeny, are discussed by Johnson et al. (1985). Detailed treatment of the Alamo Impact Event is provided by Warme and

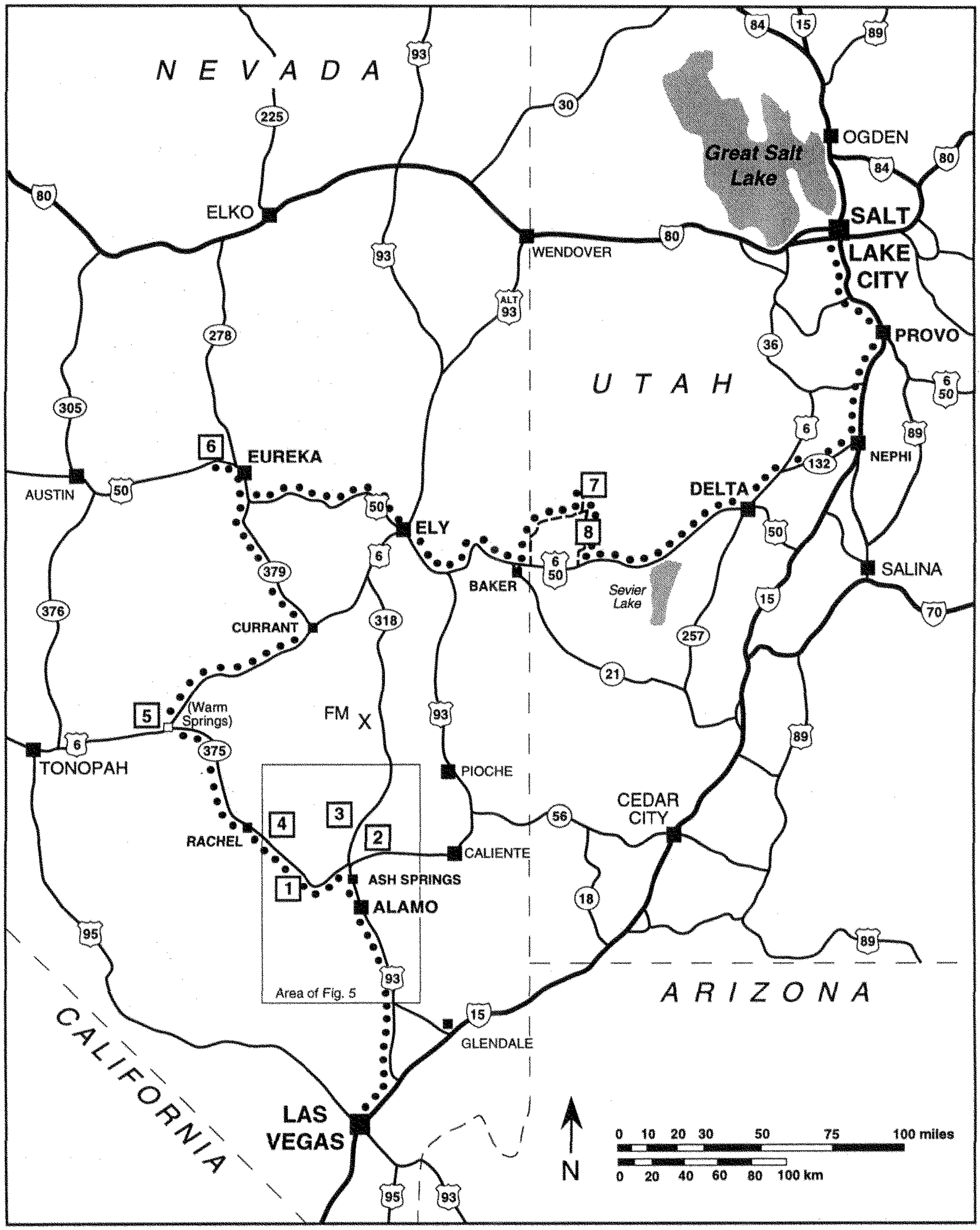


*Figure 1. Index map of Nevada and Utah, showing route of field trip (• • • •) from Las Vegas to Salt Lake City and location of Stops 1 to 8. FM, Fox Mountain, type locality of Fox Mountain Formation.*

Sandberg (1995) and a summary is provided by Warme and Sandberg (1996).


## Acknowledgments

We are grateful to the following individuals, who made preparation of our field trip guide a less onerous task: Alan K. Chamberlain, through extensive reconnaissance, provided a better knowledge of the distribution of the Alamo Breccia. Donlon O. Hurtubise provided a better understanding of the Middle Devonian rocks underlying the Alamo Breccia. Hans-Christian Kuehner generously shared his unpublished stratigraphic columns for Stops 2–4. F. G. (Barney) Poole helped the senior author measure the original stratigraphic sections, updated herein, for Stops 5–8. We also thank Keith Ketner, Paul Link, and Bill Perry for carefully reviewing our manuscript and providing helpful suggestions.

This paper was prepared as a product of Sandberg's study under the Bradley Scholar Program of the Geologic Division of the U.S. Geological Survey. The subject of this study is: "Late Devonian and Early Mississippian impact and eustatic events: Chronology, causes, and global effects."


## CONODONT BIOCHRONOLOGY

The framework for dating major Late Devonian Events of the eastern Great Basin in Nevada and the adjacent part of Utah is provided by the global Late Devonian standard conodont zonation (Ziegler and Sandberg, 1990), shown in Figure 2. The phylogenetic-zone concept employed in this zonation and its utility as a time scale were treated by Ziegler and Sandberg (1994). The duration of Late Devonian conodont zones had been estimated to average 0.5 m.y. by Sandberg and Poole (1977). This number was used by Sandberg et al. (1983) as a scale unit to date conodont zonal boundaries in approximate millions of years backward (– ~ m.y.) from a starting point of 0 m.y at the Devonian-Carboniferous (Mississippian) boundary (DCB). A tie to the radiometric time scale was intentionally avoided because of the several then-controversial dates, ranging from 345 to 360 Ma, for the boundary. Also, they pointed out a biostratigraphic problem with the original radiometric date utilized for the boundary. This problem was ignored by Harland et al. (1990) in preparation of the now-widely accepted geologic time scale (GTS 1989). These authors compounded the problem of internal Devonian dating by a misunderstanding of an earlier conodont zonation. They employed conodont zones as chrons for subdividing the Devonian but made serious errors in their method of counting zones. Their mistakes were pointed out by Ziegler and Sandberg (1994) and reiterated by Sandberg and Ziegler (1996). The finding of a new biostratigraphically controlled zircon fission-track date of 353.2

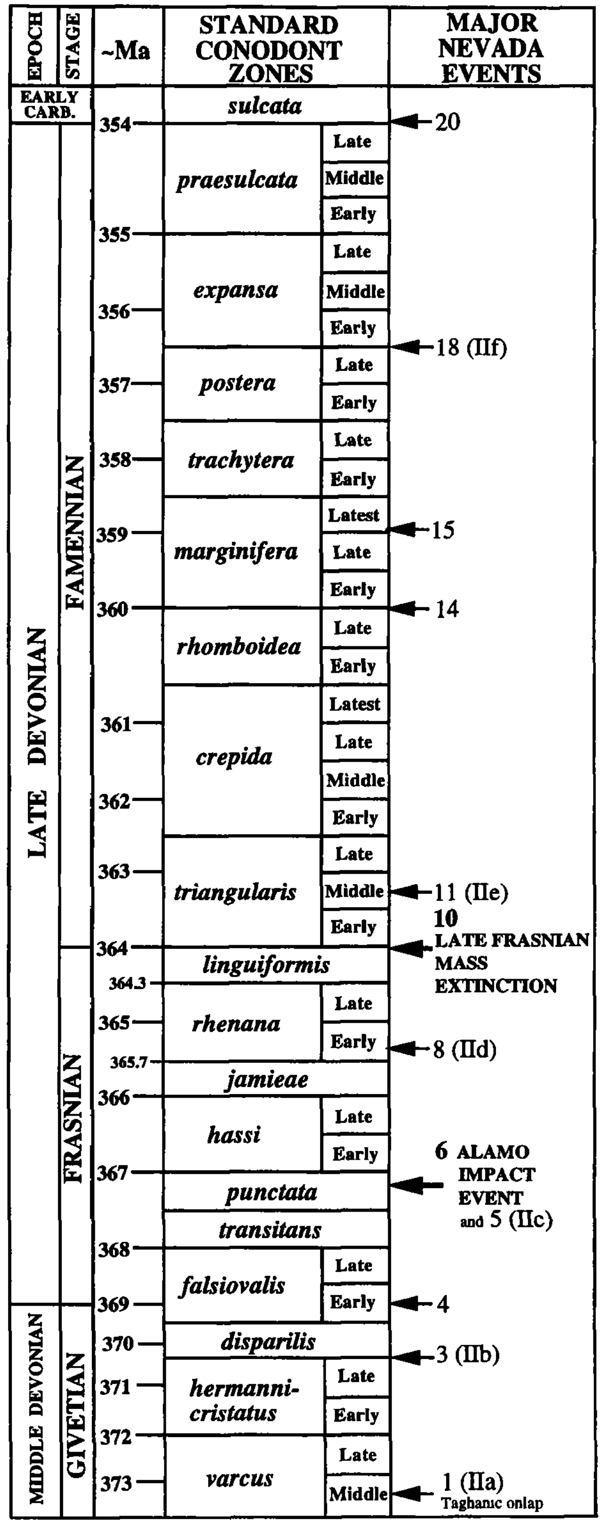


*Figure 2. Conodont biochronologic time scale showing major Middle Devonian and Late Devonian events in Nevada. See Table 1 for explanation of numbers and complete listing of all significant events. Starts of T-R (third-order) cycles of Johnson et al. (1985, 1991) shown in parentheses.*

*Table 1. Latest Middle Devonian to earliest Mississippian Events in Nevada.*

*[Eustatic and epeirogenic events modified from Sandberg et al. (1983, 1986, 1989); ~Ma recalibrated using new radiometric age of 354±4 Ma (Sandberg and Ziegler, 1996, after Claoué-Long et al., 1992) for Devonian-Carboniferous boundary in place of DCB = 0 (conodont biochronology of Ziegler and Sandberg (1990); catastrophic events added in* **Boldface**. *See Figure 2 for new conodont biochronology.]*

| | Conodont Zone | ~Ma |
|---|---|---|
| 20. Start of minor transgression during episode of continental stability | *sulcata* | 354 |
| 19. Eustatic fall | Middle *praesulcata* | 354.5 |
| 18. Eustatic rise; significant onlap of craton | Early *expansa* | 356.5 |
| 17. Regression; onset of epeirogenic uplifts | Early *postera* (?) | 357.5 |
| 16. Minor onlap; formation of narrow epicontinental seaway | Early *trachytera* | 358.5 |
| 15. Major regression; onset of continentwide erosion | Latest *marginifera* | 359 |
| 14. Major onlap; expansion of Pilot basin | Early *marginifera* | 360 |
| 13. Minor transgression; formation of carbonate banks | Middle *crepida* | 362 |
| 12. Rapid subsidence; westward spread of Pilot basin | Early *crepida* | 362.5 |
| 11. Eustatic rise | Middle *triangularis* | 363.3 |
| **10. Upper Kellwasser Event (late Frasnian mass extinction)** | ***linguiformis*** | **364.1** |
| 9. Extremely rapid eustatic rise and fall | *linguiformis* | 364.2 |
| 8. Major eustatic rise; drowning of carbonate platform and reefs | Early *rhenana* | 365.5 |
| 7. Formation of sediment-starved Pilot basin | Early *hassi* | 366.9 |
| **6. Alamo Impact Event** | ***punctata*** | **367.2** |
| 5. Sealevel rise continues; valley drowning and carbonate-platform formation extend eastward on craton | *punctata* | 367.3 |
| 4. Sealevel rise continues; new carbonate platform forms on west | Early *falsiovalis* | 369.0 |
| 3. Eustatic rise; embayments from west drown former valleys | *disparilis* (?) | 370.5 |
| 2. Sealevel fall; demise of Middle Devonian carbonate platform | Late *hermanni-cristatus* | 371.2 |
| 1. Major eustatic rise; start of Taghanic onlap of North America | Middle *varcus* | 373.2 |

Ma from bentonite deposited just after the start of the earliest Carboniferous *sulcata* Zone by Claoué-Long et al. (1992) led Sandberg and Ziegler (1996) to redate the DCB at 354 Ma and to provide a biochronologic time scale for the entire Devonian Period, giving ~Ma dates for Late Devonian conodont zonal boundaries and Middle and Early Devonian stage boundaries. These Late Devonian dates are shown in Figure 2, and dates for Middle Devonian zonal boundaries relevant to our study have been interpolated from other data. Figure 2, including the starts of T-R transgressive-regressive (third-order) cycles of Johnson et al. (1985, 1991), provides the conodont biochronologic time scale for our dating of major Middle and Late Devonian Events.

## EVENT STRATIGRAPHY

The original tabulation of late Middle Devonian to Late Mississippian eustatic events dated in DCB + or – ~m.y. was made by Sandberg et al. (1983, 1986) for the overthrust belt region of the Western United States. A revised tabulation of the 17 events pertaining only to Devonian depophase II of Johnson et al. (1985) and Johnson and Sandberg (1989) was presented by Sandberg et al. (1989). Our latest tabulation, based on recent findings, now lists 20 major latest Middle Devonian to earliest Mississippian events, numbered Events 1 to 20, and dates them in terms of both conodont zones and ~Ma (Table 1). The 12 Events that are most recognizable and most commonly observed on the field trip are plotted on Figure 2. The three most important Events, which will be discussed in more detail during field trip stops but which require a brief introduction here, are Events 6, 8, and 10.

Event 6, the Alamo Impact Event, which occurred within the *punctata* Zone at ~367.2 Ma, is now firmly established on the basis of shocked-quartz grains (Leroux et al., 1995), an iridium anomaly (Warme and Sandberg, 1995, 1996), and lapilli-like spherical carbonate ejecta discovered by H.-C. Kuehner (1997). The actual model of a offshore impact producing a splash, supertsunami, and megabreccia slide affecting the carbonate platform was prepared by Warme and Sandberg (1995, 1996) before they were aware of a theoretical model for a shallow-water impact proposed by Oberbeck et al. (1993). These models are not only closely similar but also, in some aspects, identical. Another interesting speculation pertains to rounded pebbles of charcoal, which are contained in an estuarine deposit in Wyoming (Sandberg, 1963). These pebbles were almost certainly produced by an early Late Devonian forest fire and their age is permissibly the same as the Alamo Event. Two remaining questions to be answered regarding the Alamo impact are: where was its site in present-day Nevada and what was the size and composition of the impactor? Evidence to be observed at the various stops may provide some possible answers.

The next younger major event is Event 8, a eustatic rise that occurred within the Early *rhenana* Zone at ~365.5 Ma. A paleobiogeographic lithofacies map of the Western United States (Sandberg et al., 1989, fig. 12) represents a time slice for this maximum Devonian transgression in T-R cycle IId and shows 16 localities where it has been recognized. Many other localities have since been found. In the type Devils Gate Limestone, this event is marked by a submarine discontinuity and an abrupt facies change. In and around the Confusion Range, the event is marked by the onset of the Pilot basin, whereas just to the south in western Utah, along the same strike belt, Event 6 marks the drowning of stromatoporoid reefs within the Guilmette Formation in the Burbank Hills. In Belgium, Event 8 also drowned the middle of three levels of reefs and mudmounds (Sandberg et al., 1992). Interestingly, this event coincides with the introduction of a species of the normally deep-water conodont genus *Palmatolepis* into much shallower water of the carbonate platform. The opportunistic species *Pa. semichatovae* constitutes 70–100% of *Palmatolepis* populations on the platform but <10% of *Palmatolepis* populations in basinal settings. Thus, this event is commonly located during reconnaissance study of platform sequences.

The third important event is Event 10, the Upper Kellwasser Event or late Frasnian global mass extinction, which occurred near the end of the *linguiformis* Zone at ~364.1 Ma. This event was interpreted to result from the second of two major near-collisions or actual impacts by Sandberg et al. (1988). These authors discussed the extreme eustatic sealevel changes associated with two Kellwasser Events and illustrated or discussed several key sections in Nevada and Utah, two of which will be visited on the field trip. A detailed summation and interpretation of the work of many authors on this Late Devonian mass extinction was ably presented by McGhee (1996). One interesting speculation, not previously discussed, concerns the genetic changes, bizarre mutations, and pathologic individuals observed within conodont species just before their final extinction. Could these have been produced by cosmic radiation of as yet unknown origin? If so, was this radiation, rather than an actual late Frasnian impact, the cause of mass extinction? The possible time of impact may actually have been slightly later—within the early Famennian Early *triangularis* Zone. A tsunamite of this age, present at Devils Gate, Nevada, and found at many localities in Eurasia, was previously interpreted to have been caused by the collapse of carbonate platforms during an extreme eustatic fall (Sandberg et al., 1988). But, alternatively, could it have been caused by the actual impact following several episodic, radiation-producing near misses?

## INTERPRETATION OF CONODONT BIOFACIES

Knowing that conodonts were ubiquitous in most marine environments, the possibility of using regional conodont biofacies for paleoenvironmental and paleotectonic interpretations was explored by Sandberg (1976). Using a late Famennian Zone in the western United States as a model, this paper recognized five biofacies belts between pelagic and intertidal settings. The outer four belts were each dominated by occurrences of two genera, whereas a single genus generally characterized several different biofacies, based on different microenvironmental conditions, within the innermost belt. This model has since been expanded and tested by workers in many parts of the world and has been found to be highly consistent. The outer four belts have undergone little change except for adaptation to different zonal ages. However, knowledge of the innermost belt has been expanded in a series of papers, most notably Sandberg and Dreesen (1984) dealing with the United States and Belgium, so that nine distinct nearshore biofacies are now recognized. The rules for identifying and interpreting biofacies were discussed by Sandberg et al. (1988) and Ziegler and Sandberg (1990). A detailed study of biofacies around the classic Frasnian Lion mudmound in Belgium (Sandberg et al., 1992) dealt with many of the microenvironmental conditions encountered in the innermost biofacies belt and deciphered the niche of some species.

Conodont biofacies have proven to be an invaluable tool for helping to interpret Late Devonian and Mississippian environments of deposition in the eastern Great Basin. They were also used to decipher the depth changes associated with rapid emplacement of the Alamo Breccia. Within the same *punctata* conodont Zone, rocks differing very little in age below, within, and above the Alamo Breccia proved to contain different conodont biofacies.

Here, for the first time, we present a summary chart (Table 2) showing the differences in conodont biofacies for Frasnian and Famennian times, as well as for the extraordinary, brief, post-extinction part of the earliest Famennian. This chart gives the paleotectonic settings and water depths

*Table 2. Paleotectonic settings and water depths inferred from Late Devonian conodont biofacies. [Summarized from Sandberg (1976), Sandberg and Dreesen (1984), Sandberg et al. (1988, 1992), Ziegler and Sandberg (1990). Earliest Famennian scenario applies only to faunas immediately following the late Frasnian mass extinction, which nearly wiped out the genus* Polygnathus *and resulted in telescoping of most biofacies as surviving genera filled available niches.]*

| Paleotectonic settings<br>(environments) | Continental rise, lower slopes, deepest intra-shelf basins<br>(pelagic) | Middle and upper slopes, submarine rises, deep intra-shelf basins<br>(pelagic) | Outer shelf, shallow intra-shelf basins<br>(neritic) | Inner shelf<br>(neritic) | Various shallow-subtidal and intertidal settings (dependent on type of sea bottom); hypersaline and brackish-water lagoons<br>(nearshore) | |
|---|---|---|---|---|---|---|
| Approximate water depths | 200–300 m,<br>or more | 100 m,<br>or more | 60 m,<br>or more | 10–60 m | generally 10 m,<br>or less | |
| FAMENNIAN | | | | | | |
| Biofacies | Palmatolepid or Palmatolepid-bispathodid | Palmatolepid-polygnathid | Polygnathid-"icriodid" | Polygnathid-pelekysgnathid | Clydagnathid, Scaphignathid, Patrognathid, Pandorinellinid, or Antognathid | |
| Common Abbreviations | Pa. or<br>Pa.-Bi. | Pa.-Pol. | Pol.-"icr." | Pol.-pelekys. | Clyd., Scaph., Patro., Pand., or Anto. | |
| Generic names | *Palmatolepis, Bispathodus* | *Palmatolepis, Polygnathus* | *Polygnathus, "Icriodus"* | *Polygnathus, Pelekysgnathus* | *Clydagnathus, Scaphignathus, Patrognathus, Pandorinellina, Antognathus* | |
| EARLIEST FAMENNIAN | | | | | | |
| Biofacies | Palmatolepid-icriodid | | | Icriodid | Polygnathid (?)<br>(conodonts very scarce) | |
| Common abbreviations | Pa.-icr. | | | Icr. | Pol. | |
| Generic names | *Palmatolepis, Icriodus* | | | *Icriodus* | *Polygnathus* | |
| FRASNIAN | | | | | | |
| Biofacies | Palmatolepid<br>or<br>Mesotaxid | Palmatolepid-polygnathid or Mesotaxid-polygnathid | Polygnathid-icriodid | Polygnathid-ancyrodellid | Polygnathid<br>or<br>Pandorinellinid-icriodid | Pandorinellinid |
| Common abbreviations | Pa. or<br>Meso. | Pa.-pol. or<br>Meso.-pol. | Pol.-icr. | Pol.-ancyro. | Pol. or<br>Pand.-icr. | Pand. |
| Generic names | *Palmatolepis, Mesotaxis* | *Palmatolepis, Mesotaxis, Polygnathus* | *Polygnathus, Icriodus* | *Polygnathus, Ancyrodella* | *Polygnathus, Pandorinellina, Icriodus* | *Pandorinellina* |

interpreted from conodont biofacies. It also serves as a key to the commonly used biofacies abbreviations utilized on the six columnar sections of this field guide.

## STRATIGRAPHIC SUMMARY

This summary deals with the most important stratigraphic units depicted on the cross section and columnar sections of this guide. Figure 3 is the key to lithologic symbols used in these illustrations.

### Simonson Dolostone and Western Correlatives

The Simonson Dolostone of Middle Devonian (Eifelian and Givetian) age comprises four widely used, informal members, in ascending order: the coarse crystalline, lower

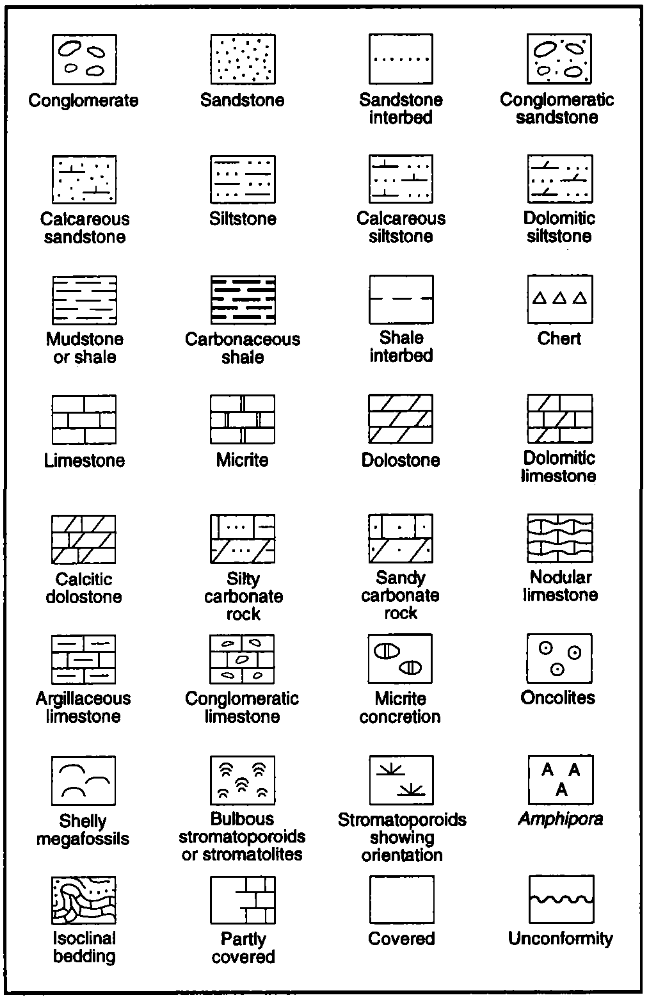


*Figure 3. Lithologic symbols used in cross section and stratigraphic columns.*

alternating, brown cliff, and upper alternating members. These members have been treated in some detail by Hurtubise (1989), Johnson et al. (1989), and especially Elrick (1995). A diagram by Johnson et al. (1989, fig. 3) depicted their westward facies change and correlation to deeper water formations. The shallow-water coarse crystalline member overlies and intertongues with the Oxyoke Canyon Sandstone. The upper and lower alternating members are mainly cyclical middle and inner carbonate platform facies with few clastic interbeds. They are separated by the brown cliff member, which represents a shoreward tongue of more open-marine stromatoporoidal and coral biostromes and packstone from the Bay State barrier to the west. This barrier produced the partly restricted environments evidenced within the alternating members. Westward, the lower alternating member grades into the Sentinel Mountain Dolostone, whereas the combined brown cliff and upper alternating members form most of the Bay State Dolostone. The brown cliff equivalent is generally thicker than the upper alternating equivalent in the Bay State. The Simonson is overlain by the Fox Mountain Formation.

### Fox Mountain Formation (new)

The Fox Mountain Formation is the lowest unit generally included in our study of the Alamo Breccia. Its top serves as a datum for measurement of the stratigraphic position of the westward-downcutting base of the breccia, as shown in Figure 4. Its base, or alternatively the contact between its two members, marks Event 1, the start of the Taghanic onlap of North America and of Devonian depophase II at ~373.2 Ma (Table 1, Fig. 2). The name Fox Mountain Formation was first used in an unpublished dissertation by Hurtubise (1989). The formation is widely recognizable, and since 1989 the name has become established in the literature. It has been used without basic definition in several papers, including Hurtubise and Sandberg (1995), Elrick (1995), and Chamberlain and Warme (1996). Because a paper planned by Hurtubise and Sandberg to formalize the name has been long delayed, the Fox Mountain Formation is here formally proposed to make it more useful for other workers.

The name Fox Mountain Formation is derived from Fox Mountain, an isolated mountain mass lying between the Seaman Range and Gap Mountain in the southeastern corner of Nye County, eastern Nevada (Fig. 1). The sequence called cliffy limestone member of the Simonson Dolomite on the east face of Fox Mountain, as described and illustrated by Hurtubise and du Bray (1992, p. B9, pl. 1), is proposed as the type section of the Fox Mountain Formation. In that area, the Fox Mountain was mapped at a 1:50,000 scale as upper, unnamed member of the Simonson by du Bray and Hurtubise (1994). The formation extends as far northeastward as the Confusion Range in western Utah, where it was mapped at a 1:48,000 scale as the lower member of the Guilmette Formation by Hintze (1974). Because of the dual assignment of the Fox Mountain, this unit was shown by Johnson et al. (1991, fig. 1) as "Basal Guilmette Fm. and (or) uppermost Simonson Dol." in the most recent version of the Devonian sea-level curve for the western United States. New stratigraphic information on the widespread distribution of the yellow slope-forming unit, forming the base of both the Guilmette Formation and Devils Gate Limestone, now precludes its assignment to the Guilmette. Widespread mappability justifies establishment of the Fox Mountain as a separate formation lying between the Simonson below and Guilmette above.

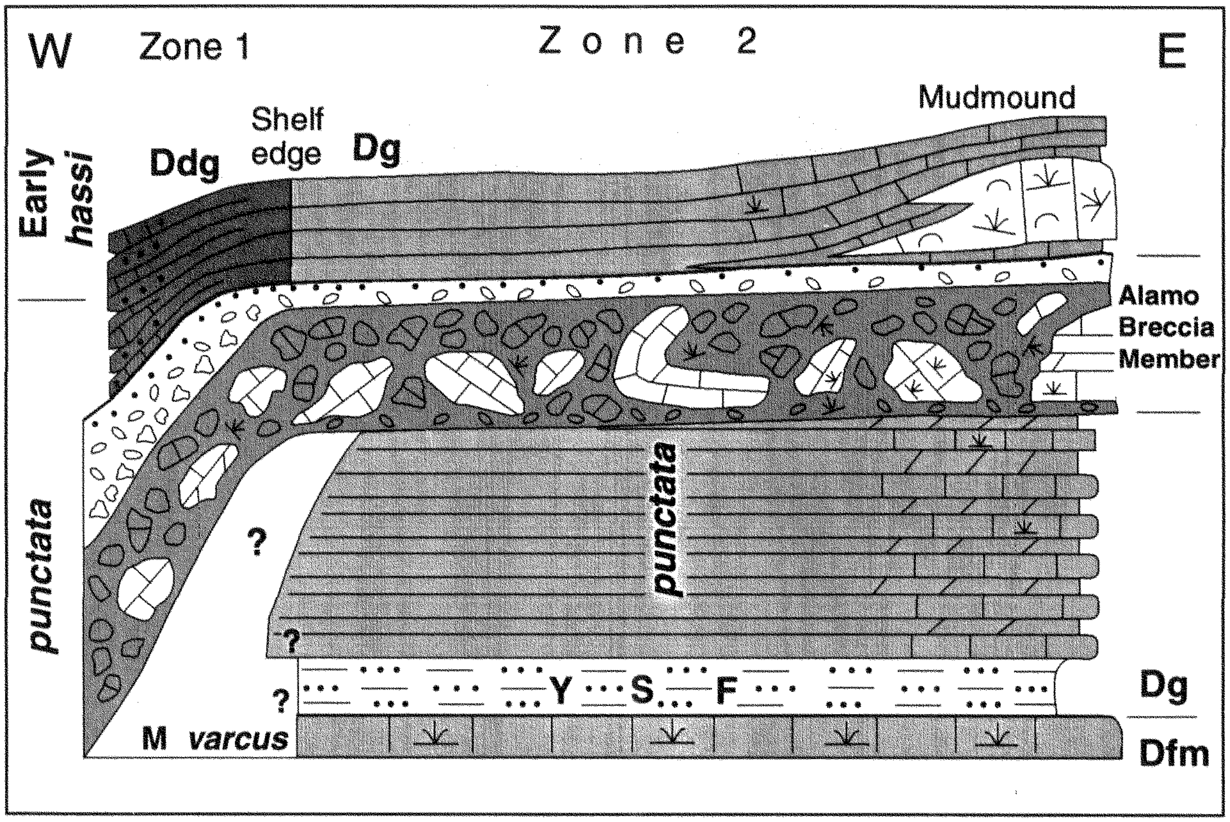


*Figure 4. Diagrammatic cross section of Alamo Breccia Member and enclosing Devonian rocks between Tempiute Mountain (Stop 4) on west and Silver Canyon (Stop 3) on east. Ddg, Devils Gate Limestone; Dg, Guilmette Formation; YSF, its yellow slope-forming member; Dfm, Fox Mountain Formation. Width of cross section is 30 km. Grass-like symbols show orientation of bulbous stromatoporoids.*

The type section of the Fox Mountain Formation of late Middle Devonian (Givetian) age is located in secs. 19 and 20, T. 4 N., R. 62 E. (unsurveyed), Nye Co., Nevada, in the Timber Mountain East 1:24,000 quadrangle (lat 38.19°E, long 115.04°N). On Fox Mountain, the type section is 76.5 m thick and comprises two members: a lower member, 47.5 m thick, consisting of nonfossiliferous, locally brecciated, evaporitic olive-gray micritic limestone; and an upper member, 29 m thick, composed mainly of interbedded open-marine olive-gray crinoidal and coralline wackestones and brachiopod packstones, including *Stringocephalus* biostromes.

The Fox Mountain Formation is distributed throughout southeastern and east-central Nevada from the Arrow Canyon Range on the south to the Cherry Creek Range on the north and in the Deep Creek Mountains, Confusion Range, and Burbank Hills of western Utah. It is generally 75 to 175 m thick but attains a maximum thickness of 200 m in the Confusion Range. A karst surface connected to cave fillings and evaporite-solution breccias in the lower member separates the two members. The basal beds of the open-marine upper member commonly fill sinkholes and channels in the top of the lower member. Where the formation is altered to dolostone, separation of the lower member from the underlying dolomitic upper alternating member is difficult, as, for example, at Silver Canyon (Stop 3), but the upper member is invariably recognizable by its high crinoidal content even where hydrothermally dolomitized, as at Hancock Summit West (Stop 1). In the area around Eureka, Nevada (Fig. 1), including Modoc Peak, just south of Devils Gate (Stop 6), and the Pancake Range to the east, equivalents of both members of the Fox Mountain are readily recognized in the upper part of the Bay State Dolostone.

## Guilmette Formation

The Guilmette Formation is not discussed in as much detail as the Fox Mountain Formation because its lithology, sedimentation, and fossil content have been treated in many previous papers, as summarized by Sandberg and Poole (1977) and Sandberg et al. (1989). Instead, we discuss only its lower part, relating to examination of the Alamo Breccia at Stops 1–4 and to proposal of this unit as a formal member of the Guilmette.

*Yellow slope-forming member.*—This member overlies the Fox Mountain Formation with apparent conformity, as shown in Figure 4. However, local, basal sandstones suggest that the contact is actually disconformable and locally unconformable. This widespread member, composed mainly of interbedded dolomitic siltstone and silty dolostone that weather to a distinctive dark yellowish-orange and yellowish-gray slope, has gone unnamed although it has been widely recognized and discussed by many workers, most recently by Hurtubise (1989), Hurtubise and Sandberg (1995), and Chamberlain and Warme (1996). Plans by Hurtubise and Sandberg to formally name the member have not yet materialized.

The yellow slope-forming member, ranging in thickness from 27 to 78 m, is invariably present wherever the base of the Guilmette Formation is exposed in eastern Nevada and western Utah. It is also present at the base of the Devils Gate Limestone around Eureka, Nevada (Fig. 1), where it is 68 m thick. The disconformity at its base represents Event 2, the demise of the Middle Devonian carbonate platform, and the member itself represents Event 3, the start of a new transgression (T-R cycle IIb), at 370.5 Ma. Above its locally sandy base, the next unit of the member is invariably an evaporitic sabkha dolostone overlain by algal laminite and biostromal limestone formed by columnar, digitate stromatolites. Overlying beds of siltstone and dolostone and thin interbeds of pelmicrite commonly contain tubes of the peritidal worm *Spirorbis*, and in the Burbank Hills, Utah, serpulid worm mounds are present. All these features, together with the absence of conodonts in lower beds and their scarcity in upper beds, attest to the brackish and highly saline environments of this peritidal unit, at the start of a slow eastward transgression.

*Carbonate-platform facies.*—The carbonate-platform facies above the yellow slope-forming member has an average thickness of about 100 m, but this decreases westward as it is bevelled and finally truncated by the Alamo Breccia. The lower contact of this facies is gradational to the yellow slope-forming member through an interval of 10 to 20 m in which the thickness and number of yellow-weathering silty dolostone interbeds decrease progressively upward. The base is placed at the first thick bed of olive-gray limestone, commonly a pelmicrite. The carbonate-platform facies consists mainly of shallow-subtidal to intertidal, interbedded oncolitic, stromatoporoidal, coralline, and nodular, olive-gray pelmicrite, micrite, and biopelmicrite, containing common calcispheres and ostracodes and fewer brachiopods. These beds alternate with thinner beds of supratidal yellowish-gray silty dolostone and algal laminite. In the deepening, upper part, bulbous stromatoporoids become abundant and commonly form patch reefs. These stromatoporoidal beds continues upward into the large, unrotated slide blocks that are incorporated into the lower part of the Alamo Breccia. The carbonate-platform facies of the Guilmette is similar to the upper alternating member of the Simonson Dolostone but light-colored interbeds are subordinate, whereas they make up nearly half of the latter.

*Alamo Breccia Member (new).*—The name Alamo breccia has been used informally in several papers since 1991, e.g., by Warme and Sandberg (1995, 1996), who described the model for its emplacement. The Alamo Breccia Member is here formally proposed as a member of the Guilmette Formation. It is also considered a member of the Devils Gate Limestone, the western, deeper water equivalent of the Guilmette. The Alamo Breccia originated as the product of Event 6, the shallow-marine impact of an extraterrestrial object, possibly an icy fragment from a comet. The member was deposited within a few days as the result of a large splash, followed instantly by the impact, which fractured and delaminated the carbonate platform, and ensuing supertsunamis, which decreased in intensity as they reverberated back and forth across the ocean basin.

The Alamo Breccia is divided laterally into three zones, of which the western two, Zones 1 and 2, contain megabreccias and turbidites ranging in thickness from 55 m to 110 m. Zone 2, forming the widest areal belt of the member, lies entirely on the carbonate platform, whereas Zone 1 occupies the foreslope west of the shelf edge (Fig. 4). The areal distribution of Zones 1 and 2, entirely within Lincoln County, and the location of field trip Stops 1–4 are shown in Figure 5. In an as yet incompletely delimited semicircular outer belt lie the much thinner, only 10 m to <1 m thick, possibly discontinuous, graded litharenite deposits of Alamo Breccia Zone 3. These litharenites resulted partly from bits of carbonate rock stranded at the high-water line of the supertsunamis and partly from fallout of the original splash and secondary waterspout. The rock fragments were then sorted as flood waters ran back seaward. Two corroborated localities of Zone 3 lie in adjacent Nye County (Fig. 5). One of these, north of the map area of Figure 5, is Fox Mountain (Fig. 1). There, the graded litharenite of Zone 3 is only 0.9–1.5 m thick and is enclosed within supratidal algal laminites. At Devils Gate (Stop 6), a lithologically similar bed, only 0.3 m thick, may be an isolated remnant of Zone 3.

The type section of the Alamo Breccia Member, illustrated and described in Figure 6, is at Hancock Summit West. A complete description of the location is given under

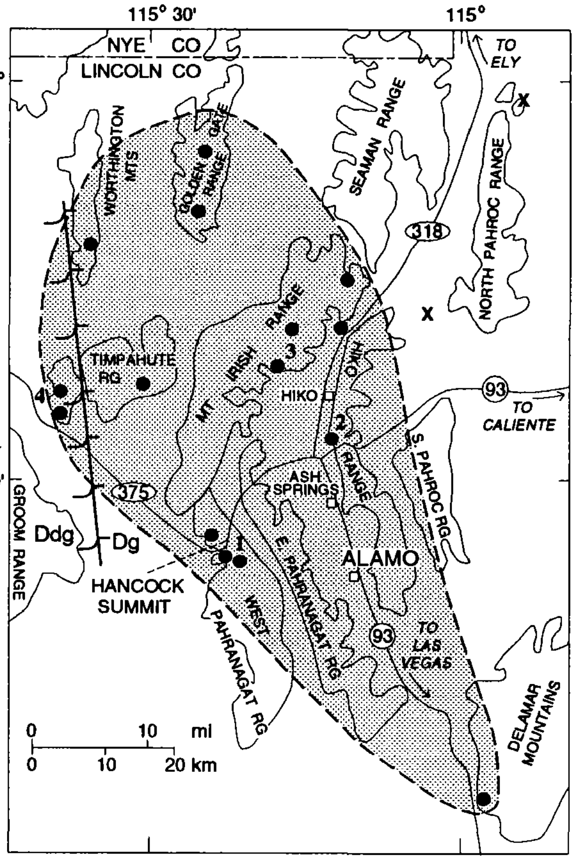


*Figure 5. Index map showing distribution of the Alamo Breccia and studied localities (•) in zones 1 and 2 (shaded area), field trip localities 1 to 4, the Late Devonian shelf edge between the Guilmette (Dg) carbonate platform and the Devils Gate (Ddg) slope, and nearby localities (X) in zone 3 (not shaded).*

Stop 1. The name Alamo is derived from the only major town lying within the area of distribution of the member.

At its type section, the Alamo Breccia of early late Frasnian (*punctata* Zone) age is 59 m thick (Fig. 6). There and elsewhere within Zone 2, the member comprises four units, labelled A to D in descending order, because only Units A and B are invariably present. Unit A is part of a series of well-organized, normally graded turbidites deposited by tsunamis of decreased intensity. Unit B, deposited by the initial supertsunami, is a disorganized debrite composed of large, rotated blocks. Unit C is synonymous with the huge slide blocks of carbonate-platform bedrock, as much as 500 m long and 30 m thick, barely separated by the relatively thin Unit D from underlying intact beds. Some C blocks are essentially parallel to bedding of the underlying carbonate platform, whereas others are peels, produced by downslope movement of other C blocks, similar to peels produced by a wood plane. Unit D, preserved only beneath blocks of Unit C, is 0–5 m thick in the type section. It is mainly light-gray-weathering calcareous diamictite representing fluidized bedrock. Along strike, Unit D abruptly changes from intact to fractured bedrock, to a melange of isolated and rotated fragments, and ultimately to diamictite.

In eastern sections, the Alamo Breccia Member is overlain by carbonate-platform rocks similar to those that underlie it. However, at the type section and other western localities, the overlying beds, composed of sandy, nodular, crinoidal calcarenite and biomicrite, represent a moderately deep-water slope facies (Fig. 6), because excavation by the impact had instantaneously lowered the floor of the carbonate platform at least 60 m. The slope facies contains conodonts of the palmatolepid-polygnathid biofacies, whereas those of the underlying carbonate-platform facies belong to the shallow pandorinellinid biofacies (Fig. 6, Table 2). Intervening conodont faunas of the litharenitic breccia matrix are generally highly mixed shallow- and deep-water biofacies. Following a shallowing-upward interval of 35 m at Stop 1 to as little as 17 m elsewhere, carbonate slope rocks give way to a sequence of shallow-water, craton-derived, bypass sandstones interbedded with sandy pelmicrite. In some eastern sections, organic buildups, such as the stromatoporoidal Mount Irish mudmound (Stop 3) or coral patch reefs (in the Hiko Hills, north of Stop 2), were developed a short interval above the breccia. These resulted from lesser shoreward depression of the carbonate platform, permitting framework building organisms to survive and grow upward toward their pre-Alamo Event water depths.

## Devils Gate Limestone

The type area of the Devils Gate Limestone is at Devils Gate pass, which is Stop 6 of the field trip. The formation was named by Merriam (1940), who did pioneering paleontologic work on its faunas, primarily the brachiopods and corals, but did not describe a type section. The measurement and description of a type section were done by Sandberg and Poole (1977, fig. 5). Their section subsequently was updated and refined by Sandberg et al. (1989, fig. 9). Because the lower part of the type section is not exposed, its equivalency to the Guilmette Formation has heretofore been uncertain. Now, however, with the finding of the yellow slope-forming member on the north slope of Modoc Peak, only 7 km south of the type section, we are able to document that the base of the Devils Gate is identical to that of the Guilmette Formation, its shallow-water equivalent. Thus, both formations are of Middle Devonian (late Givetian) and Late Devonian (Frasnian and early Famennian) age. Higher members of the type Devils Gate are treated in the discussion of Stop 6. At Tempiute Mountain (Stop 4), the Devils Gate is entirely

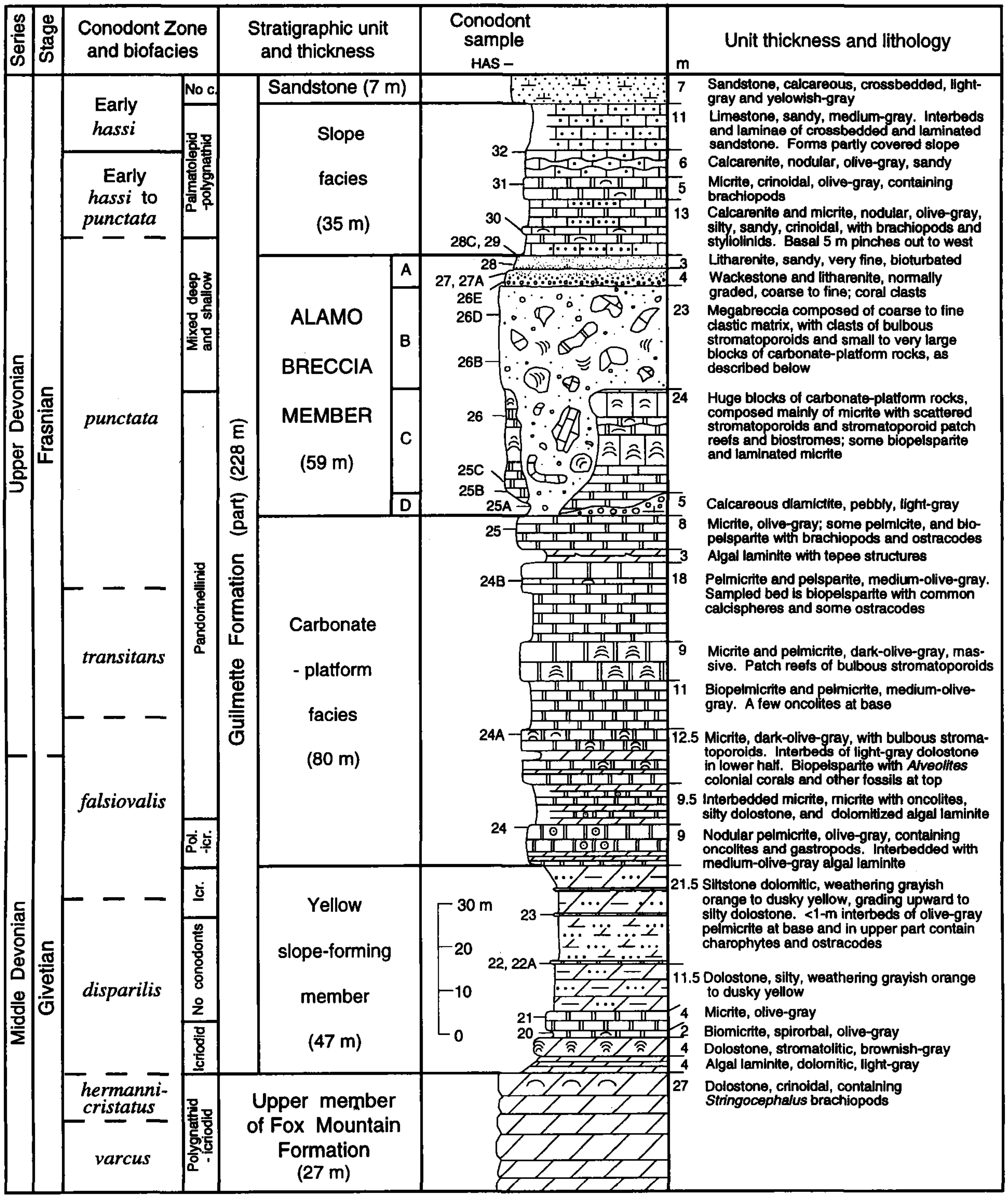


*Figure 6. Stratigraphic section of upper member of Fox Mountain Formation and lower part of Guilmette Formation, showing type section of Alamo Breccia Member, at Hancock Summit West (Stop 1), West Pahranagat Range, Nevada. Shows position of 24 conodont samples.*

Late Devonian (Frasnian and early Famennian) in age. This age difference is because both the yellow slope-forming member and carbonate-platform facies equivalent in the Devils Gate Limestone are missing there due to shelf-margin collapse and truncation by the Alamo Breccia Member (Fig. 4).

*Alamo Breccia Member.*—This member forms the base of the Devils Gate on the foreslope west of the carbonate platform (Fig. 5) and rests on brecciated Middle Devonian Bay State Dolostone. The Alamo Breccia Member on the west slope of Tempiute Mountain is at least 107 m thick and locally may be much thicker. Units C and D are absent, and the member comprises a thick, disorganized debrite of Unit B overlain by a thick, well-graded turbidite or turbidites of Unit A. The member is overlain by turbiditic siltstone, mudstone, silty micrite, and sandstone of the Devils Gate, containing a deep-water fauna. This fauna includes radiolarians, conodonts, styliolinids, hexactinellid sponge spicules, and entomozoan ostracodes. One of these entomozoans was identified as *Ungerella multicostata* by J.-G. Casier (written commun., Nov. 6, 1996).

## Pilot Shale

The Pilot Shale of Late Devonian (early Frasnian) to Early Mississippian (Kinderhookian) age comprises three totally unrelated members of different ages. Their separate histories have been largely masked because collectively they are weakly resistant and generally form a slope between the cliff-forming Guilmette Formation and correlatives below and the Lower Mississippian Joana Limestone above. Thus, it was convenient for early workers to map them as an undivided Pilot Shale.

*Lower member.*—The lower member of the Pilot Shale is the most interesting and tectonically significant of the three members. Its sedimentation and the origin and expansion of the Pilot basin through time have been analyzed and mapped in great detail by Sandberg and Poole (1977) and Sandberg et al. (1989). The initial Pilot basin in east-central Nevada was small and nearly circular in shape. Its formation, Event 7, resulted from tectonic downwarping within the Guilmette carbonate platform. It is attractive to think of the bullseye shape of this initial basin as the target site for the Alamo Impact, but shock features do not occur beneath it and its earliest sediments are dated as Early *hassi* Zone, ~0.3 m.y. younger than the Alamo Breccia (Table 2). Instead, it may be related to early Antler orogeny, whose start might be more nearly coincident with the Alamo Impact Event. Through its early history in the Frasnian and earliest Famennian time, the Pilot basin was sediment starved, as demonstrated by biostratigraphically well-constrained cross-section models (Sandberg and Poole, 1977, fig. 7; Sandberg et al., 1989, fig. 10). During its later episodes of expansion in the early Famennian, locally coincident with Events 8, 12, and 14, the Pilot basin subsided rapidly in response to sediment load as silty and sandy turbidites and occasional carbonate debris flows poured in from all sides. Along the east side of the Pilot basin from Alamo, Nevada, northeastward to the Burbank Hills, Utah, just south of Stop 8 (Fig. 1), medium-dark-gray, turbiditic and debris-flow, nodular limestone of the mostly early Famennian West Range Limestone was deposited on the slope between the Pilot basin and the Guilmette carbonate platform. Although the base of the lower member is everywhere conformable, and in some places gradational, with the underlying Guilmette Formation, West Range Limestone, or Devils Gate Limestone, its upper contact with the Leatham Member is marked by the greatest Late Devonian unconformity in North America and generally records a time gap of ~3.5 m.y.

*Leatham Member and upper member.*—The middle, Leatham Member, although much thinner than either the lower or upper members, records a complex history. Its lower unit consists of a thin basal conodont-bearing lag sandstone, recording Event 18, an Early *expansa* Zone eustatic rise at ~356.5 Ma, overlain by much thicker black chert that locally encloses large concretions, which yield a deep-water conodont fauna. The middle part consists of another thin lag sandstone containing conodonts of the next younger, Middle *expansa* Zone, overlain by an algal oncolite-sponge-brachiopod biostromal limestone that is part of a much-described shallow-water bank extending from Montana to southern Nevada (e.g., Sandberg and Poole, 1977; Gutschick and Rodriguez, 1979). In Utah, this bank has been dated as Early *praesulcata* Zone. The highest unit of the Leatham is a shallow-water brachiopod-bearing calcareous siltstone, having the same distribution as the oncolite bed and recording Event 19, a eustatic fall in the Middle *praesulcata* Zone at ~354.5 Ma.

The upper member of the Pilot is a deeper water slope facies composed mainly of turbiditic calcareous siltstone and silty limestone. Its base marks Event 20, a minor transgression in the earliest Kinderhookian *sulcata* Zone at ~354 Ma. At and around Stop 8, olive-black shale at the base of the upper member occupies a submarine channel and rests with apparent disconformity on the Leatham Member. Regionally, however, the basal contact is an unconformity. At Okelberry Pass in the Conger Range, 17 km southwest of Stop 8, the upper member has truncated most of the Leatham and rests directly on its basal lag sandstone.

## Woodruff Formation

The transitional facies Woodruff Formation (Poole and Sandberg, 1993) is observed only at Stop 5. There, it is

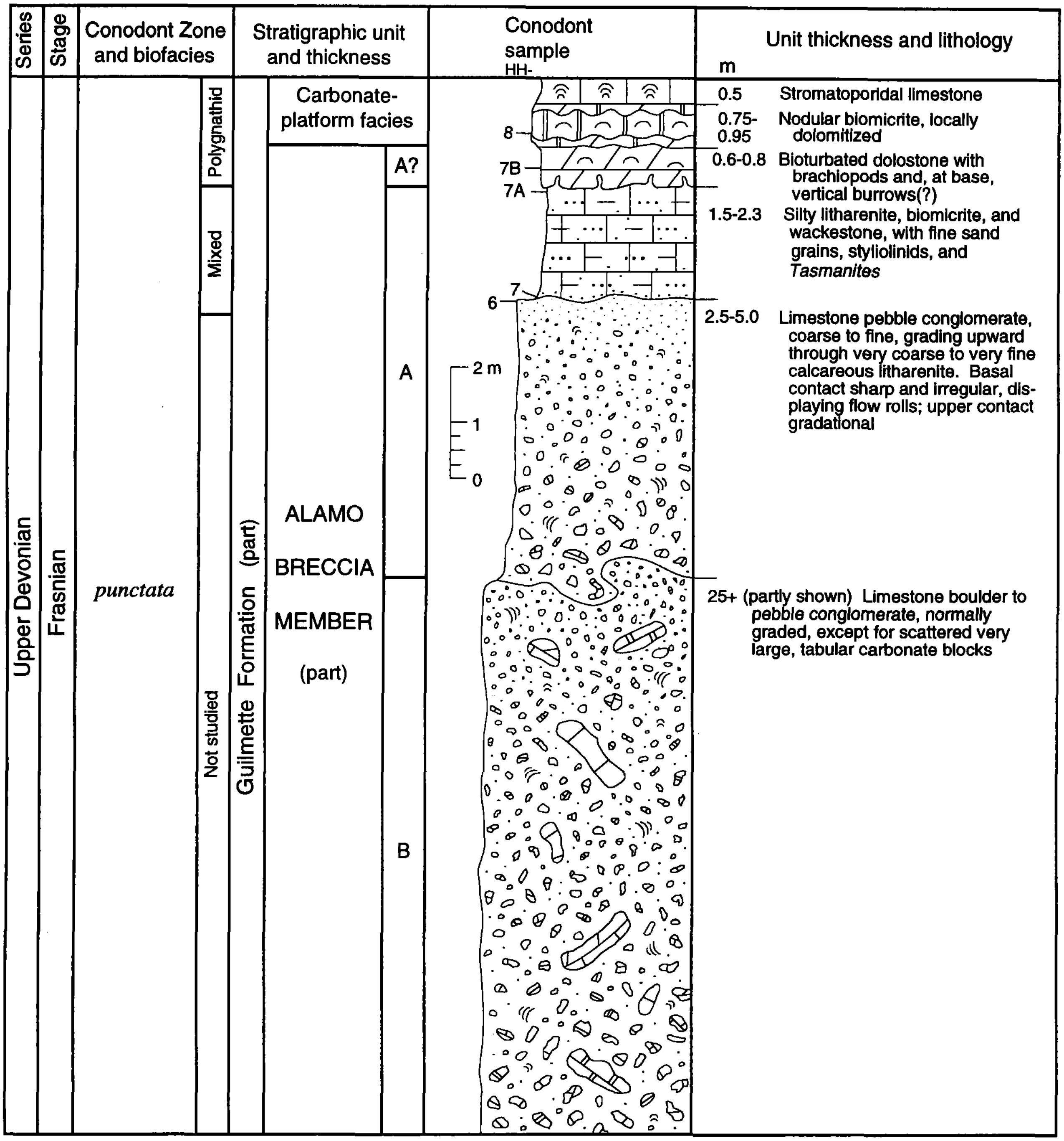


*Figure 7. Stratigraphic section of highest part of Alamo Breccia Member of Guilmette Formation at Hiko Hills South (Stop 2), just north of U.S. Highway 93 and 2 km northeast of junction with Nevada Highway 318, Hiko Range, Nevada. Samples HH-6, HH-7, and HH-8 collected at complete, main section, 0.73 km to north-northwest.*

mainly black radiolarian chert interbedded with siltstone. The Woodruff occupies a narrow, 50-km-wide belt extending 400 km from northeastern to southwestern Nevada. Regionally, it intertongues westward with the oceanic, western-facies Slaven Chert. In some areas, the upper, Frasnian to Famennian part of the Woodruff is lithologically similar to the lower member of the Pilot Shale. Where the upper Woodruff is composed mainly of siltstone, it has been commonly misidentified as Pilot, but its siltstones are more siliceous and spiculitic. The Woodruff basin lies generally west of the Pilot basin, but in one area, west of Devils Gate (Stop 6), a narrow strait may have connected the two basins. An unconformity within the upper part of the Woodruff, present in the Warm Springs area east of Stop 5, is probably the same as that below the Leatham Member of the Pilot, but its magnitude is less.

### Overlying Mississippian units

The upper member of the Pilot Shale is overlain unconformably by the Joana Limestone of Early Mississippian (Kinderhookian and Osagean age). A thin, clastic unit at its base may contain burrowed calcareous sandstone, crinoidal sandstone, quartzite, siltstone, and sandy limestone. Regionally, the Joana cuts downward and may rest on lower Pilot, West Range Limestone, or Guilmette Formation. However, where the Joana overlies Kinderhookian Narrow Canyon Formation, the contact is conformable. The next higher bed of Joana is nodular wackestone, succeeded by crinoidal banks and mudmounds, then deeper water biomicrites becoming cherty toward the top. Overall, the Joana Limestone represents a carbonate bank that formed west of the Mississippian carbonate platform on the east side of the Antler flysch trough (Sandberg et al., 1983; Poole and Sandberg, 1991). This bank continued to grow as the trough subsided tectonically, so that Joana sedimentation became progressively deeper through time.

At Stop 8 in the Confusion Range, Utah, the Joana Limestone is overlain by the Delle Phosphatic Member at the base of the Chainman Shale. A complete section of Chainman Shale in this area is illustrated by Sandberg et al. (1980, fig. 4). Beyond the western edge of the Delle, the next higher, Needle Siltstone Member of the Chainman overlies the Joana. Farther west, as at Tempiute Mountain (Stop 4) and in the Pancake Range and Diamond Mountains, east of Eureka, Nevada (Fig. 1), the Joana is overlain paraconformably to unconformably by turbiditic radiolarian-rich and spiculitic micrites, encrinites, and crinoidal wackestones of the Tripon Pass Limestone. These were shed westward from an eastward-migrating welt, ahead of the Antler flysch trough. Mississippian flysch of Osagean age is commonly termed Dale Canyon Formation.

## FIELD TRIP STOPS

Field trips Stop 1 to 8 are discussed sequentially. Stops 1 to 4 on the first two days will deal with aspects of Event 6, the Alamo Impact. These are located in Lincoln County, southern Nevada, and the county geologic map by Tschanz and Pampeyan (1970) serves as a useful, but not infallible, guide. Stops 5 and 6 on the third day, farther west and north in Nevada, feature mainly evidence for Event 10, the late Frasnian mass extinction, but they also show the horizon where Event 6 may occur. Stops 7 and 8 on the fourth day, in and near the Confusion Range in west-central Utah, show Events 8, 10, 11, 12, 18, and 20 (Table 1).

### Hancock Summit West (Stop 1)

Location and access: On west edge of West Pahranagat Range, 0.2 km south of Nevada Highway 375, 3 km southwest (and 2.3 highway miles west) of Hancock Summit, in the N1/2 SE1/4 sec. 19, T. 6 S., R. 59 E. (unsurveyed), Lincoln Co., Nevada, on the Crescent Reservoir 1:24,000 quadrangle (lat 37.41°N, long 115.40°W). At end of guard rail, drive south onto dirt road that forks left to gravel pile or right down arroyo. Measured section begins at arroyo and extends up hill to south. Upper part of Alamo Breccia Member is cleanly exposed just beyond gravel pile in washout resulting from flash flood. Large rounded quartzite boulder, containing Native American petroglyphs depicting desert bighorn sheep, marks west side of this exposure.

Discussion: Stop 1 is depicted by Figure 6, illustrating the sequence from the upper member of the Fox Mountain Formation to the basal part of the sandstone unit in the Guilmette Formation above the Alamo Breccia. This sequence contains the type section of the Alamo Breccia Member and spectacularly illustrates its four units, Units A to D, which characterize this and other sections within its wide, lateral Zone 2. Detailed descriptions of these vertical and lateral units by Warme and Sandberg (1995, 1996) are based primarily on this section.

Visitors have two choices, and a large party may be split into two groups. One group may: (1) first examine small clasts in the bare face of Unit B of the Alamo Breccia, just above the parking area at the east end of the outcrop; (2) climb to the top of the breccia and examine the overlying sequence; (3) follow the upper contact of Unit A uphill westward to a prominent rocky point; (4) examine sigmoidal blocks within Unit B south of the point; (5) descend westward into the saddle to examine the contact between the yellow slope-forming member of the Guilmette and the Fox Mountain; (6) sidehill eastward to examine Alamo Unit D; (7) drop back down into the arroyo at the base of the yellow slope-forming member; and (8) finally, walk up the arroyo back to the parking area.

A second group or independent visitor wishing to examine the sequence in stratigraphic succession, should reverse the route, first walking down the arroyo to the conspicuous yellow slope-forming member and ending just above the parking area. The most interesting features to be observed are described in this direction. Walking down the arroyo, the base of the Alamo Breccia is covered on the hillside, but several large angular blocks within Unit B are noteworthy. At the intersection of the strike belt of the yellow slope-forming member of the Guilmette

Formation, *Stringocephalus* occurs near the top of the underlying Fox Mountain Formation. Tightly packed biostromes of this terebratulid brachiopod, however, as well as the thin stromatolite bed just above the base of the yellow slope-forming unit, are best exposed on the west side of the saddle in the ridge that lies due south. Do not proceed directly in this direction, but walk uphill following the gully that heads southeast across strike and bear to the left. The carbonate-platform facies of the Guilmette contains many beds of olive-gray pelmicrite that contain the shallow-water biota described in Figure 6, interbedded with light-gray dolomitized algal laminite. This facies becomes more stromatoporoidal toward the top. Approaching the cliff-forming part of the hillside, the visitor will encounter the light-gray carbonate diamictite of Unit D of the Alamo Breccia. This thin unit can be followed along strike for some distance to observe its many changing lithologies and thicknesses, but observe that its basal contact parallels bedding. The next higher ledge- and cliff-forming unit, 24 m thick, with many stromatoporoids, including patch reefs, is actually detached from the underlying carbonate platform and forms part of a huge Unit C block! Next, walk southwest climbing gently to reach the saddle formed by the yellow slope-forming member. Then, climb to the top of the cliff-forming Unit B of the Alamo Breccia at the prominent point and observe the structures along the southeast slope. Next, follow the cliff top of Unit A down its strike belt to the northeast, taking care to observe its contact with overlying beds of the Guilmette. At the marked measured section close to the end of this belt, the beds above the apparent top are better exposed and another 3 m of slope formed by fine sandy litharenite will be recognized to be part of the turbidite cloud belonging to the breccia. The presence of an open-marine fauna in overlying nodular micrite and crinoidal wackestone beds signals the start of deposition of post-Breccia beds. Remember this relationship, when you visit Stop 2. Next, turn downhill within the bare exposure of Unit B toward the parking area and observe the abundant stromatoporoids and the different lithologies of small blocks that are enclosed within the fine matrix, which itself is actually a fine litharenite, composed of much smaller fragments of limestone.

### Hiko Hills South (Stop 2)

Location and access: At south end of Hiko Hills, north of U.S. Highway 93 and 2.75 km due northeast of junction with Nevada Highway 318-375, in the SE1/4 SE1/4 SW1/4 sec. 36, T. 4 S., R. 60 E., Lincoln Co., Nevada, on the Hiko 1:24,000 quadrangle (lat 37.56°N, long 115.20°W). Turn north off highway 1.2 mi east of junction on dirt road past west side of borrow pit and drive to its end at mouth of small canyon. Measured section begins a short distance (from end of road, elapsed time 10 minutes; elevation gain 120 ft) up canyon and extends northward.

Discussion: The sequence to be observed during a short visit by a large group comprises only the upper part of Unit B of the Alamo Breccia, all of Unit A, and its well-exposed contact with the overlying carbonate-platform facies, as shown in Figure 7. For the independent investigator, who can allot an entire day for a visit, a better strategy is to park beside the saddle within the ridge to the north before reaching the end of the road. Then, hike 1.25 km northward across many small gullies before reaching the first east-northeast-trending canyon that leads to a complete exposure of Units D, C, B, and A of the Alamo Breccia, and its contact with overlying beds. In this area, at least 100 m of carbonate-platform facies below the Alamo is exposed, but not the basal yellow-slope forming member of the Guilmette. Climbing above the Breccia, the visitor will be rewarded by being able to observe several hundred meters of carbonate-platform facies displaying coralline beds, including colonial-coral patch reefs, and several interesting channel-fill sandstones. If using the generalized geologic map of Lincoln County (Tschanz and Pampeyan, 1970), the visitor should be aware that the Guilmette Formation in this area is incorrectly mapped as Sevy Formation and Simonson Dolomite.

The short section (Fig. 7) to be visited at Stop 2 was chosen, not only because of easy access, but also because it dramatically illustrates the problem of locating the exact top of Unit A of the Breccia at many sections of Zones 1, 2, and 3. Walking up the gully, note that the top 25 m of Unit B is generally well graded. Normal grading is interrupted only by a few, large angular blocks, emplaced at odd angles. Observe only the ridge to the west (left). The ridge to the east is post-Breccia Guilmette downdropped on a high-angle normal fault. At the end of the gully, note the sharp contact between Units B and A, which represents a separate turbidite, on the ridge to the northwest. The contact is highly irregular and these irregularities are interpreted as syndepositional flow rolls. Climbing out of the gully, the clear exposure of the gradational contact with the overlying, much finer, turbiditic litharenite should be observed. The next higher unit of bioturbated dolostone, which ranges from 0.6 to 0.8 m in thickness in the Hiko Hills, is assigned questionably to Unit A of the Breccia. The overlying ledge of nodular biomicrite, grading upward to stromatoporoidal limestone, clearly represents the start of the open-marine post-Breccia sequence. The same two beds, yellowish-gray bioturbated dolostone overlain by medium-dark-gray nodular biomicrite, both of about the same thickness, are also present at Stops 1 and 3.

The unanswered question is whether the generally dolomitized bed represents the highest turbidite of the

Breccia, which, because of its high oxygen content and rich nutrients, was extensively colonized by burrowing organisms, or whether the bed represents the initial deposit of the post-Breccia sequence, perhaps composed of Breccia detritus that was later transported and redeposited by currents. Because of the marked lithologic change and the more widespread dolomitization of the lower bed, we favor the upper contact, whereas H.-C. Kuehner, who has studied the same outcrop, favors the lower contact of this 0.6- to 0.8-m-thick bed. The visitor is encouraged to discern other features that may help resolve this minor difference in interpretation.

### Silver Canyon (Stop 3)

Location and access: On hill east of dirt road, on north side of Silver Canyon in Mt. Irish Range, in the SW1/4 sec. 3, T. 4 S., R. 59 E. (unsurveyed), Lincoln Co., Nevada, on the boundary between the Mount Irish SE (on south) and Mail Summit (on north) 1:24, 000 quadrangles (lat 37.625°N, long 115.35°W). To reach contact between Alamo Breccia Member and Mt. Irish mudmound, drive north on Nevada Highway 318 for 2.5 mi beyond its junction with Nevada Highway 375 and exit westward on dirt road through barbed-wire gate. Proceed up alluvial fan on rough, cobbly road for 8.3 mi, continuing past left fork to Mt. Irish Petroglyph Site, and park about 1.3 mi beyond this fork. Walk up ridge to north and turn east onto saddle extending to hill capped by mudmound (from road, elapsed time, 80 minutes; elevation gain, 700 ft).

Discussion: The full sequence of Middle Devonian (Eifelian) to Lower Mississippian (Osagean) rocks exposed at and east of Stop 3 in the Mount Irish Range and farther south in the East Pahranagat Range is illustrated by a time-rock chart (Fig. 8), which can later be compared with the chart showing the different stratigraphic succession present farther west, at and above Stop 4. To observe the entire sequence in the area east of Silver Canyon would consume at least two full days of arduous hiking. However, the sequence from the Simonson Dolostone through the beds just above the Mount Irish mudmound can be traversed in a full day by starting on the second, more prominent knob, 1 km east of the parking area for Stop 3. That traverse should be directed northward as far as the cliff formed by the upper part of the Alamo Breccia. Then, offset a short distance to the west, before climbing up the steep canyon to the contact between the Alamo Breccia and the overlying Mt. Irish mudmound at the precise location that will be reached by a more gentle approach from the west on the organized field trip. The Mt. Irish mudmound and its relation to the Alamo Breccia are shown diagrammatically in Figure 4. An oblique aerial photograph (Fig. 9) shows in succession: a bedded, large C block of the Alamo Breccia; a cliff formed by Units B and A of the Breccia; the light-colored mudmound; and a sequence of post-mound beds to the top of the hill. The Alamo Breccia in this area was originally interpreted as bioherm detritus by Dunn (1979), who studied the Mt. Irish mudmound.

On the field trip, while climbing northward on the east side of the ridge, observe the large blocks within the Alamo Breccia. After reaching the saddle and while walking eastward along its south side, be sure to note the well-graded aspect of the conglomeratic lower part of Unit A of the Breccia and an unusual large, apparently thin, pancake-shaped clast. Along the crest of the saddle, this important sequence is exposed, in stratigraphic succession: (1) limestone grit, 90 cm thick, representing a higher turbidite of Unit A, with a large *Alveolites* coral content, caused by more buoyant fossil fragments having floated upward during deposition; (2) very coarse to fine graded litharenite of Unit A, 70 cm thick; (3) dolomitized, laminated, bioturbated, fine litharenite, 30 cm thick, equivalent to the controversial bed at Stop 2; (4) medium-dark-gray nodular limestone, 45 cm thick, also present at Stop 2, representing the probable base of the post-Breccia sequence; (5) limestone, 1.2 m thick, with tabular and small, round stromatoporoids; and (6) yellowish-gray calcareous sandstone and siltstone and sandy, silty limestone, 3 m thick. Approaching the east side of the saddle and turning south along the west side of the hill containing the mudmound, this post-Breccia sequence intertongues with light-gray mudmound rock. Turning eastward and at the head of the first steep canyon, the visitor may want to climb over and examine the lower part of the 58-m-thick mudmound.

The stratigraphic interval from the base of the Alamo Breccia Member to the top of the Fox Mountain Formation at Stop 3 (Fig. 8) is 156 m. This compares to 127 m for the same interval farther west at Hancock Summit West (Fig. 6) and to only 98 m at Monte Mountain South, much farther west and only 14 km east of Stop 4. The westward decrease of this interval demonstrates our evidence for interpreting the Alamo Breccia as truncating section westward (Fig. 4).

Driving westward to Stop 4, the two humps of Bactrian Mountain are conspicuous features north of Nevada Highway 375, a short distance west of Crystal Spring. The upper part of the Guilmette Formation, forming the east hump, has been studied by Morrow (1997) as part of his dissertation. A columnar section showing the sequence of West Range Limestone in the saddle and Pilot Shale on the east side of the west hump has been published by Sandberg and Ziegler (1973, 1993) and Sandberg and Poole (1977).

### Tempiute Mountain (Stop 4)

Location and access: Along abandoned mine road, 0.3 km north of Tempiute historic site, in the NE1/4 sec. 11 and

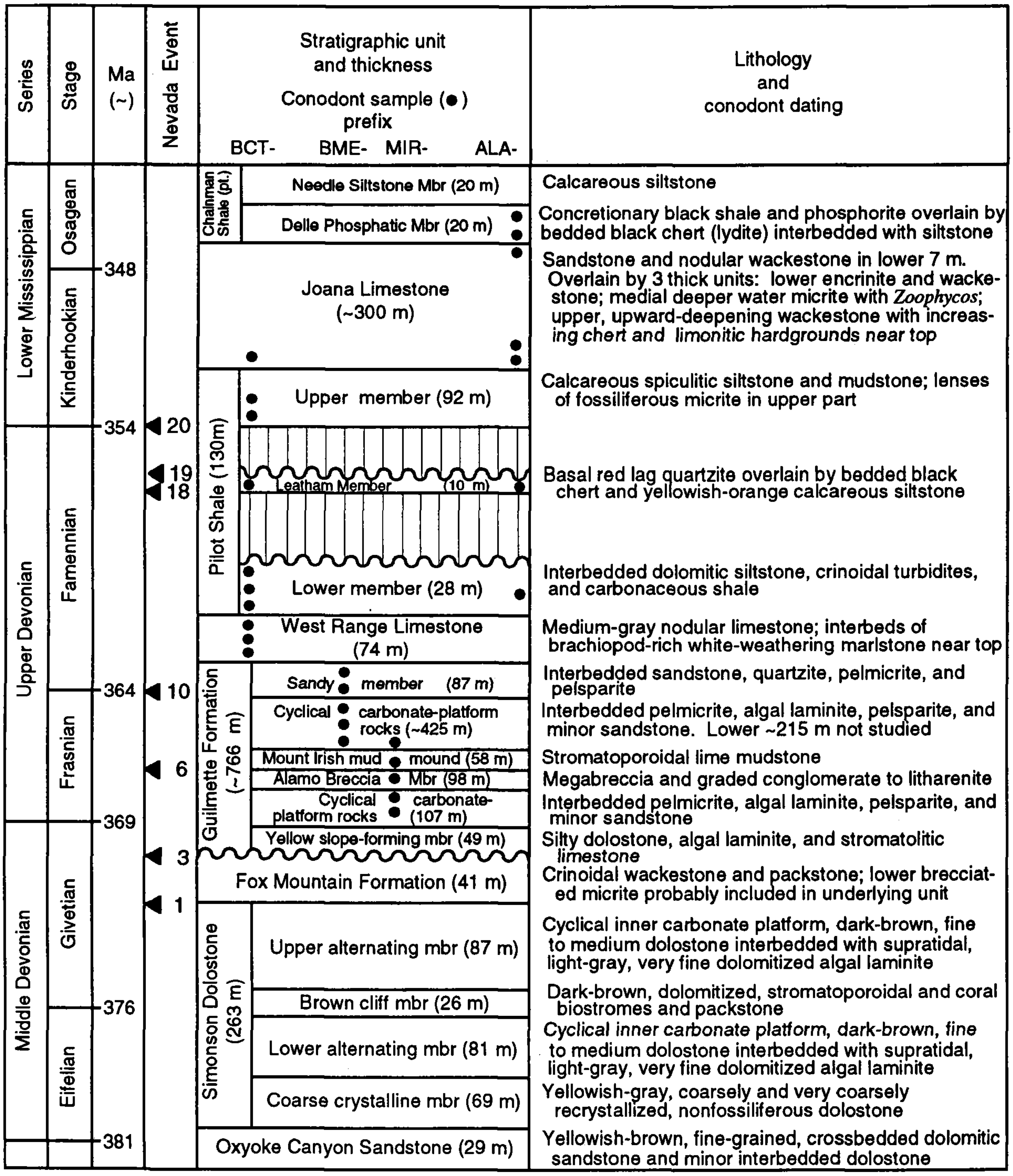


*Figure 8. Time-rock chart of Middle Devonian to Osagean stratigraphic units exposed at Alamo Canyon (ALA) and Bactrian Mountain (BCT), East Pahranagat Range, and at Silver Canyon (MIR), Mount Irish Range, east and north of Alamo Nevada. Compiled from field notes, measured sections, and reconnaissance sections of H.-C. Kuehner, J. R. Morrow, F. G. Poole, and C. A. Sandberg and from columnar section of West Range Limestone and Pilot Shale at Bactrian Mountain (Sandberg and Ziegler, 1973, 1993; Sandberg and Poole, 1977). Conodont samples prefixed BME from East Bactrian Mountain provided by Morrow; others (location indicated by prefix initials) provided by Sandberg. New Ma dates for Devonian stage boundaries are from Sandberg and Ziegler (1996). See Table 1 for explanation of Nevada Events and Figure 2 for their more precise dating. Time values of Alamo Breccia Member, Leatham Member, and mudmound are exaggerated for graphic purposes. Thicknesses of Fox Mountain Formation and older units are from Chamberlain and Warme (1996, table 2). Mount Irish mudmound and Alamo Breccia Member are exposed north of dirt road into Silver Canyon (Stop 3), Mount Irish Range.*

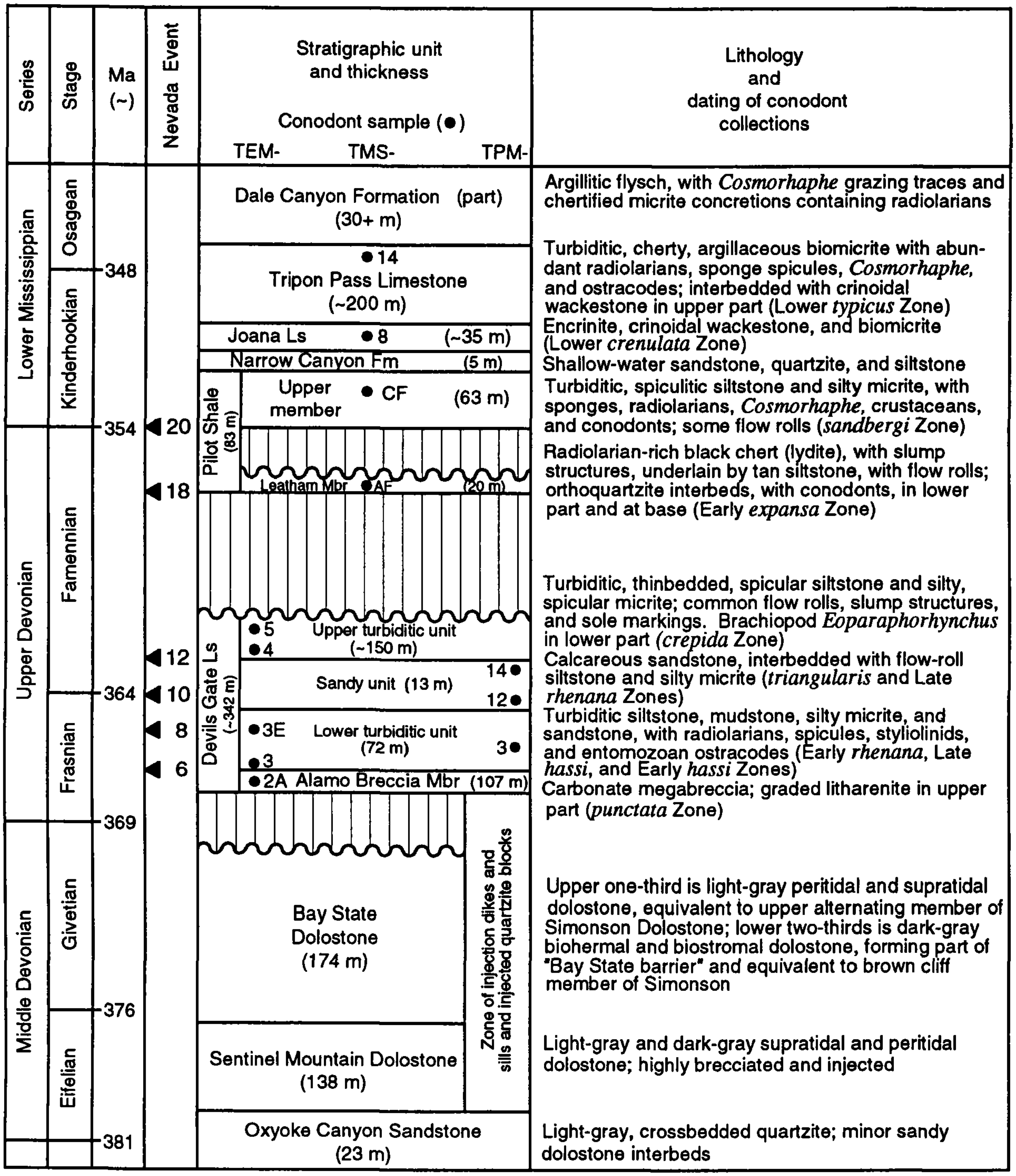


*Figure 10. Preliminary time-rock chart of Middle Devonian to Osagean stratigraphic units exposed along Tempiute Mountain, at west end of Timpahute Range, east of Rachel, Nevada. Compiled from field notes, measured sections, and reconnaissance sections of H.-C. Kuehner, J. R. Morrow, F. G. Poole, and C. A. Sandberg. Except for presence of Alamo Breccia and Leatham Member and absence of lower member of Pilot Shale, named stratigraphic units in this sequence are identical to those in northern Pancake Range, east of Devils Gate, Nevada. Conodont samples prefixed TPM provided by Morrow; others provided by Sandberg. New Ma dates for Devonian stage boundaries are from Sandberg and Ziegler (1996). See Table 1 for explanation of Nevada Events and Figure 2 for their more precise dating. Time values of Alamo Breccia Member, Leatham Member, and Narrow Canyon Formation are exaggerated for graphic purposes. Most accessible locality to examine zone of injected sandy rocks is above mine road at Tempiute Mountain South (Stop 4).*

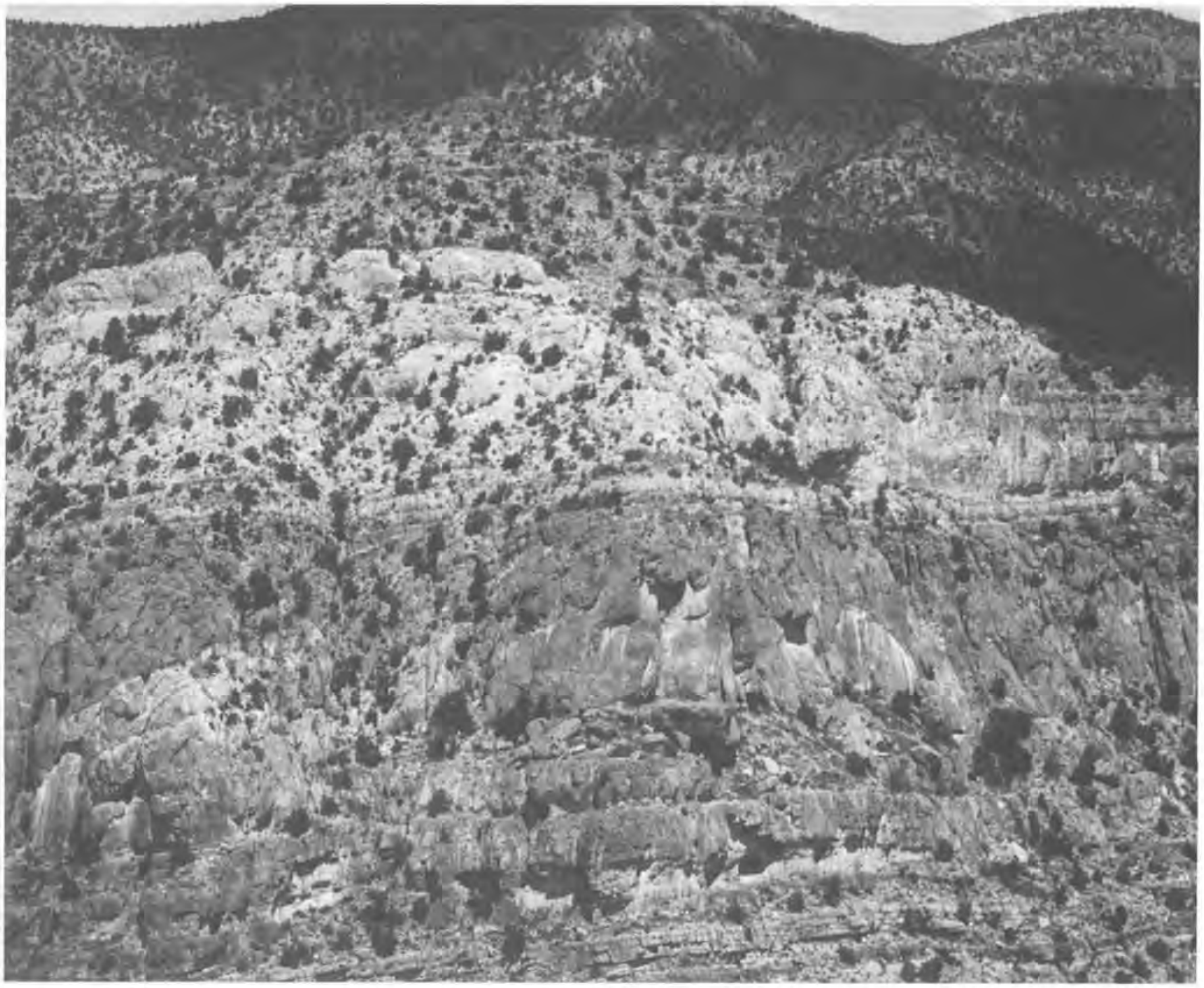

*Figure 9. Oblique aerial photograph of part of Guilmette Formation, showing cliff-forming Units B and A of Alamo Breccia Member overlain by light-colored Mt. Irish mudmound, at Stop 3 on north side of Silver Canyon, east side of Mt. Irish Range, Nevada (Kodachrome slide furnished by A. K. Chamberlain).*

(or) NW1/4 sec. 12 (unsurveyed irregular sections), T. 4 S., R. 56 E., Lincoln Co., Nevada, on the Tempiute Mountain South 1:24,000 quadrangle (lat 37.62°N, long 115.64°W). To reach ridge with injected quartzite slabs, dikes, and sills in Middle Devonian sequence below Alamo Breccia, exit Nevada Highway 375 to east on dirt road 3.0 mi northwest of Coyote Summit. Drive eastward for 1.4 mi to road fork and continue northeast on left fork on road that turns southeast at range front and continues up gravelled arroyo to south, ending at canyon mouth, 1.7 mi beyond fork. Walk up canyon on trail along washed out mine road through ruins of Tempiute. Turn northward on mine road that switches back to east and continue beyond mine shaft to point overlooking Tempiute (from end of road, elapsed time, 35 minutes; elevation gain, 400 ft).

Discussion: The full sequence of Middle Devonian (Eifelian) to Lower Mississippian (Osagean) rocks exposed on Tempiute Mountain in the vicinity of Stop 4 is illustrated by a time-rock chart (Fig. 10). This chart should be compared and contrasted with the chart (Fig. 8) for the easterly sequence observed at Stop 3. Tempiute Mountain is a high, north-trending mountain mass at the west end of the east-trending Timpahute Range, from which it is separated by a major eastward-directed thrust fault (Tschanz and Pampeyan, 1970). The sequence shown on Figure 10 was measured at four localities that are not as easily accessible as

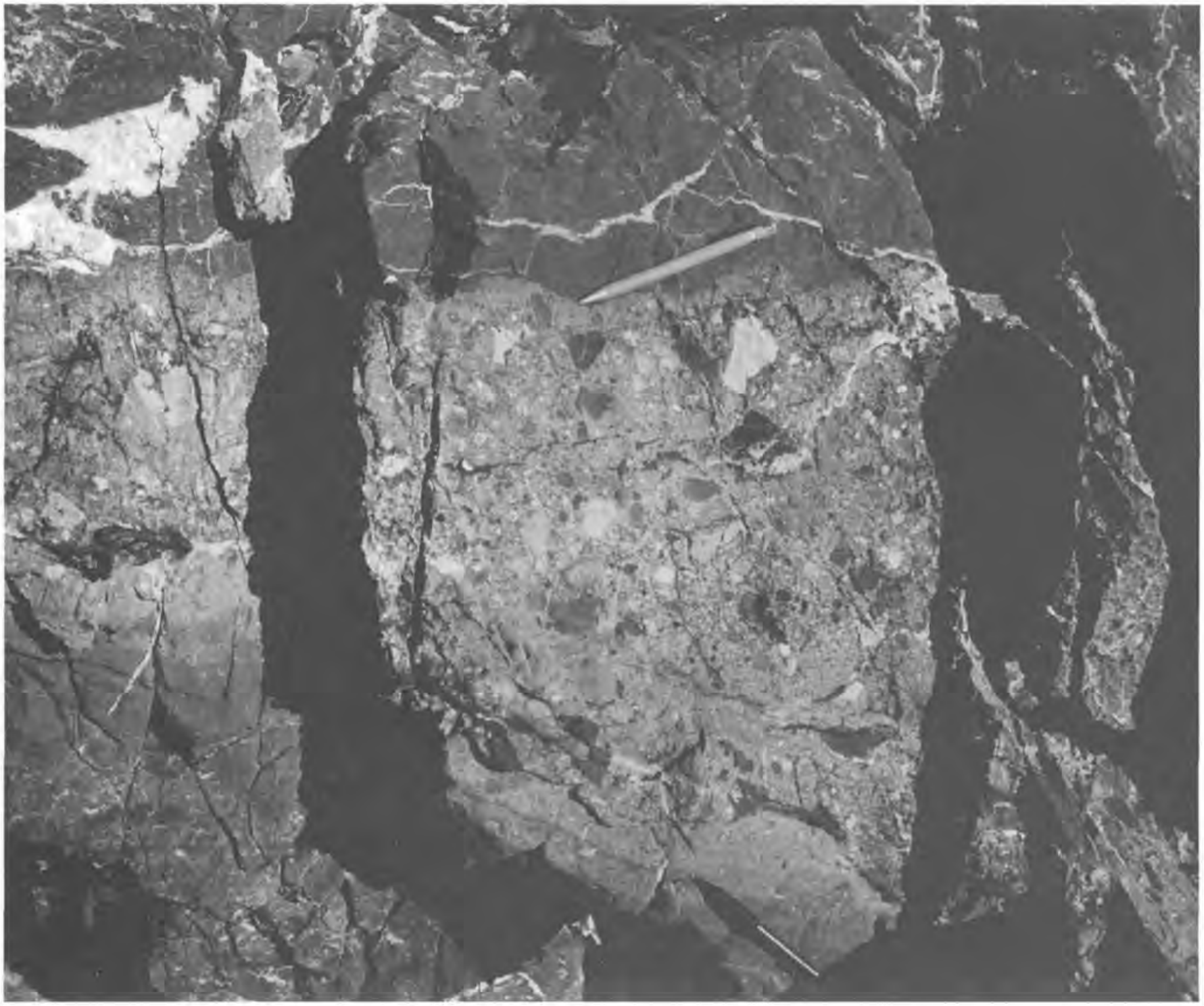

*Figure 11. Photograph of impact-related, zoned injection sill within Middle Devonian rocks near Stop 4 on Tempiute Mountain, west end of Timpahute Range, Nevada (Kodachrome slide furnished by H.-C. Kuehner).*

Stop 3. Viewing these localities would take another 1–2 days each. The Middle Devonian sequence below the Alamo Breccia was measured twice starting on the main ridge seen north of the access road on entering the arroyo leading to Stop 4. One measured section ends at Grants Peak and the other at Coyote Peak. The Devonian sequence above the Alamo Breccia and the lower part of the Mississippian sequence were measured on the ridge crest trending eastward from Coyote Peak and on the ridge crest at the head of the next major canyon south of the one approaching Stop 4. The higher part of the Mississippian sequence was measured above a trail flanking the east side of Tempiute Mountain.

The purpose of Stop 4, however, is to examine and interpret the injection features in the sequence below the Alamo Breccia, so far observed only at this locality, and to ponder their relation to the Alamo Impact site. Walking up the canyon, an excellent exposure of the Oxyoke Canyon Sandstone can be examined. This ledge-forming unit strikes uphill and crosses the mine road just beyond Stop 4. Along the road, just before Stop 4, is a shaft where a large injected block of Oxyoke Canyon quartzite, mineralized by malachite, was mined out. Extending up the ridge at Stop 4, just beyond, is a series of breccia-filled injected dikes and sills similar to the sill illustrated in Figure 11. Both dikes and sills are commonly zoned, with fine rims encasing coarse cores, containing fragments of carbonate and quartzose siltstone and sandstone. Although the matrix resembles that of the Alamo Breccia in being a carbonate litharenite, it differs in being very quartzose. The clastic dikes and sills are interpreted to have been injected by transient, abnormally high fluid pressures from below through fractures resulting from the Alamo Impact. Casual visitors might interpret these features to be related to range-front faults, but similar phenomena have not been seen along range fronts elsewhere in Nevada.

The paleotectonic position of the Tempiute Mountain section, on the Late Devonian foreslope west of the shelf margin (Fig. 4), is now firmly established (Warme and Sandberg, 1995, 1996). The question remains as to whether the sequence below the Breccia represents crater rim, as might be interpreted from the theoretical model of Oberbeck et al. (1993), or whether the crater site lies farther west. A major factor in our favoring the latter alternative is the thickness of the sedimentary sequence below the Alamo Breccia. In comparing the total thickness of Middle Devonian formations between the Oxyoke Canyon Sandstone and the base of the Devils Gate or Guilmette formations, the difference between 312 m at Tempiute Mountain (Fig. 10) and 304 m at Silver Canyon (Fig. 8) is insignificant. The only difference then devolves to the thickness of the lower part of the Guilmette Formation, totalling 156 m at Silver Canyon. However, this interval has already decreased westward to 98 m, 14 km east of Tempiute Mountain. Thus, the missing section at Stop 4 might originally have been only 75 m or less. The removal of this thin section would not suggest a very deep crater if the impact site were at or west of Tempiute Mountain. Thus, the extraterrestrial object could not have been very large, or the impact site must have been farther west. We favor the latter hypothesis because a small impact, even though very close, is unlikely to have caused such extensive damage to the platform.

### Warm Springs South (Stop 5)

Location and access: On west side of ridge, 0.55 km north of U.S. Highway 6, in the SW1/4 SE1/4 NE1/4 sec. 25, T. 4 N., R. 49-1/2 E., Nye Co., Nevada, in the Warm Springs NW 1:24,000 quadrangle (lat 38.18°N, long 116.39°W). To reach measured section, drive 2.4 mi south and west on U.S. Highway 6 from T-junction at end of Nevada Highway 375 at abandoned site of Warm Springs. Just west of knob of volcanic rocks, turn north onto dirt trail that crosses arroyo and then turns eastward. Park in saddle behind knob and walk northward down into and up narrow canyon for about 10 minutes to base of folded chert sequence on ridge to west (left).

Discussion: Study of the structurally complex Warm Springs area at the south end of the Hot Creek Range was initiated by F. G. Poole, who requested the collaboration of the senior author in dating the Devonian and Mississippian rocks. A preliminary report (Poole and Sandberg, 1992) suggested that this area represented the eastern edge of the Roberts Mountains allochthon overlapped by Mississippian deep basinal baritic deposits and calcareous turbidites. Subsequent collection of more than 40 conodont samples has necessitated a slightly different interpretation. These samples show that the area was one of progressive deepening and that an interpretation of Devonian thrusting is unnecessary. In the Warm Springs area, Lower Paleozoic rocks as young as the Lone Mountain Dolostone of Silurian and Early Devonian age were part of a carbonate platform that extended much farther west but backstepped eastward through time. Tectonic deepening began late in Early Devonian or in early Middle Devonian time. Lower Middle Devonian (Eifelian) rocks of the Denay Limestone are mainly lower-slope deposits of turbiditic styliolinid- and tentaculitid-bearing argillaceous limestones interbedded with sedimentary barite. Upper Middle Devonian (Givetian) rocks of the same formation are mainly debris-flow deposits composed of talus from coral reefs such as are exposed in the Reveille Range to the southeast. Upper Devonian (both Frasnian and Famennian) cherts and siltstones of the Woodruff Formation (Poole and Sandberg, 1993) are transitional-facies rocks. The siltstones enclose slide blocks (olistoliths) derived from the carbonate platform to the east, whereas the interbedded black radiolarian ribbon cherts (lydites) are tongues of the deep-basinal Slaven Chert that was deposited farther west.

The Warm Springs South section demonstrates three major phenomena associated with the Alamo Event (Event 6) and Upper Kellwasser Event (Event 10): (1) Evidence of the Alamo Event is virtually nonexistent in the mountain ranges of central Nevada. Invariably, rocks much older than the Alamo Breccia are overlain by rocks much younger than the Alamo Breccia. This may be partly explained by widespread uplift, possibly initiated by post-impact isostatic rebound. Contributing to this hiatus may be the removal of rocks by the Alamo impact or subsequent tsunamis. The area of missing Devonian section extends from the Inyo Mountains in southeastern California to the Carlin gold-bearing trend in northern Nevada. (2) Deep-slope and basinal sedimentation was much slower than carbonate-platform sedimentation (by a factor of at least 1:10) and thus produced greatly condensed rock sequences. (3) Evidence of tsunamites associated with impacts at or around the Upper Kellwasser Event (10) are invariably masked by the great water depth and deposition was essentially uninterrupted.

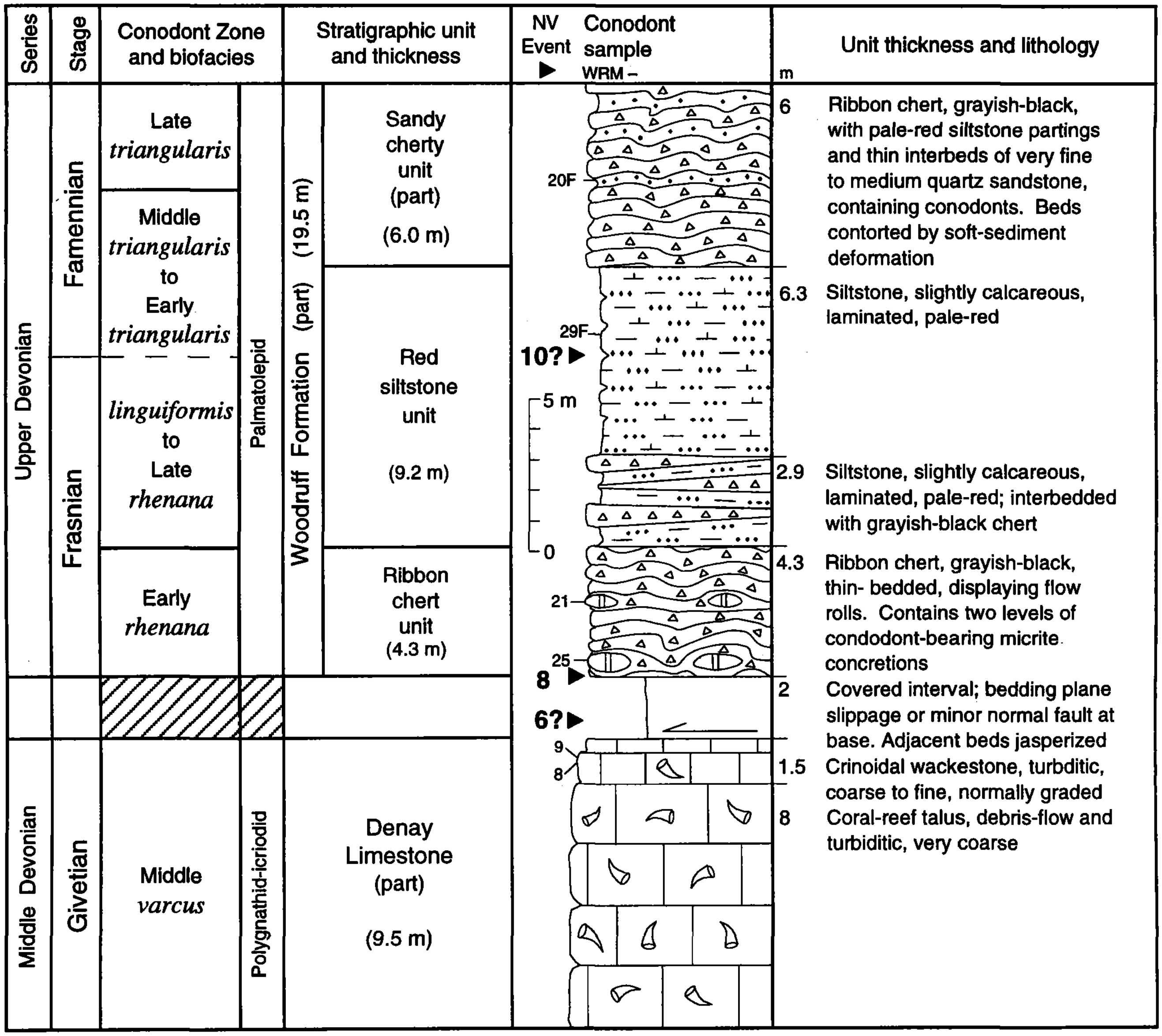


*Figure 12. Stratigraphic section of uppermost part of Denay Limestone and lowermost part of Woodruff Formation at Warm Springs South (Stop 5), southern Hot Creek Range, Nevada. Shows close proximity of approximate positions of Alamo (6?) and Upper Kellwasser (10?) Events in deep-water, transitional-facies Devonian rocks. WRM-20F and WRM-29F, bedding-plane-chip, rather than acid-dissolution, samples both contain large percentage of reworked Frasnian conodonts.*

Because of the lack of direct evidence for exactly positioning Events 6 and 10, their approximate positions are questioned in the stratigraphic column (Fig. 12) depicting the measured section at the Warm Springs South (Stop 5) locality. These positions, which can be no farther than 12.5 m apart, however, are narrowly bracketed by well-dated conodont samples from enclosing beds. Middle Devonian beds below Event 6 are well dated as Middle *varcus* Zone by abundant conodont faunas in turbidites and debris flows shed from reefs. Beds above Event 10 are well dated as Late *triangularis* Zone by conodonts on bedding surfaces of thin interbeds of fine- to medium-grained turbiditic sandstone. Event 8, the eustatic deepening within the Early *rhenana* Zone, is marked by the intervening sequence of deep-water black radiolarian ribbon chert (lydite), containing two horizons of micrite concretions. A few of these concretions are not silicified and yield conodonts useful for dating and biofacies analysis.

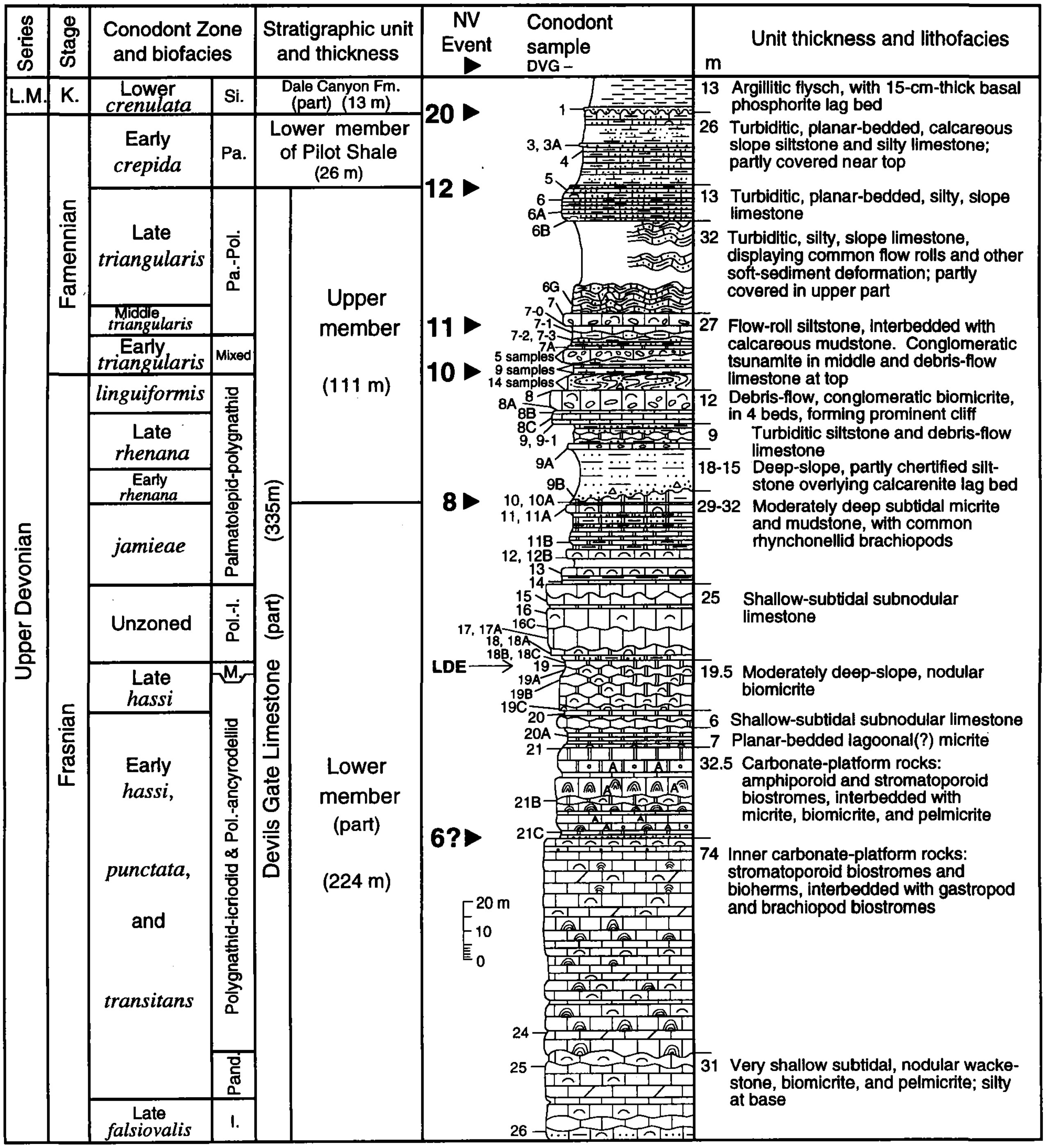


*Figure 13. Stratigraphic section of Devils Gate Limestone and Pilot Shale at Devils Gate (Stop 6), along U.S. Highway 50, 13 km northwest of Eureka, Nevada. Updates stratigraphic columns shown by Sandberg and Poole (1977, fig. 5) and by Sandberg et al. (1989, fig. 9). Event 6 is questionably represented by a 0.3-m graded calcareous diamictite with teepee structures at top. Event 8 is well represented by a submarine disconformity overlain by conodont-rich lag bed. Detailed sampling adjacent to Events 10 and 11 is shown by Figure 14 and an enlarged columnar section and conodont biofacies analysis of selected samples across the Frasnian-Famennian boundary is shown by Figure 15. Event 20 is included within an unconformity representing time gap of ~15 m.y. LDE, maximum of local deepening event at sample DVG-19; may be tectonically controlled or as yet unrecognized at other localities of Devils Gate Limestone and Guilmette Formation. L.M., Lower Mississippian; K., Kinderhookian. Si., siphonodellid biofacies; M., mesotaxid biofacies.*

Devils Gate (Stop 6)

Location and access: On north side of U.S. Highway 50 in Devils Gate pass, 8 road miles northwest of town of Eureka and 5 road miles west of junction with Nevada Highway 278. Measured section is just north of abandoned stretch of old highway, providing ample parking space, in the SW1/4 SW1/4 SW1/4 sec. 24, SE1/4 SE1/4 SE1/4 sec. 23, and N1/2 N1/2 NE1/4 sec. 26, T. 20 N., R. 52 E., Eureka Co., Nevada, in the Devon Peak 1:24,000 quadrangle (lat 39.57°N, long 116.07°W). Main section (Fig. 13) was measured from top to bottom, for 0.8 km from east to west, starting on the hill slope below alaskite sills, offsetting across a series of small-throw normal faults, and ending at road level at covered base of Devils Gate Limestone west of pass. Parking just west of second exit to old highway, most complete (Fig. 14) of three measured sequences across Event 10, the late Frasnian mass extinction, is situated above top of low cliff to east (right). Evidence for Event 8, the Early *rhenana* Zone eustatic rise, is located west of the trail leading to this exposure. The thin candidate bed for Event 6, the Alamo Impact Event, is at top of high cliff (Fig. 13) extending from road level at west end of pass. It is more easily accessed from west end of old highway.

Discussion: The complete sequence of Upper Devonian and Lower Mississippian rocks measured mainly on the north side but also, for the highest part, on the south side of Devils Gate pass is shown in a columnar section (Fig. 13). This section updates earlier versions published by Sandberg and Poole (1977, fig. 5) and Sandberg et al. (1989, fig. 9). Newly discovered, possible evidence for the trace of Event 6 far to the north of other occurrences will be visited by the organized field trip, time permitting. Otherwise, if part of the group is interested mainly in this Event, they may proceed directly to this exposure, while the main group examines the many other interesting features, closer to the road, in the middle of the outcrop belt on the north side of the pass. Possible evidence for Event 6 is a 29-cm-thick bed of slightly sandy, graded, calcareous diamictite with granule-size carbonate clasts, and, in the top 8–10 cm, parallel laminations and tepee structures. Elsewhere, similar thin beds characterize Zone 1 of the Alamo Breccia.

The most interesting sequence to be seen at Devils Gate is the main section across Event 10, the late Frasnian mass extinction, the global distribution and interpretation of which have been treated by Sandberg et al. (1988) and McGhee (1996). This sequence, detailed in Figure 14, begins above a hardground developed at sample DVG-8, overlying a series of four cliff-forming debris-flow beds, shown in Figure 13. The deep-slope environment preserves the best record so far observed in North America of the eustatic and biotic changes centered around Event 10.

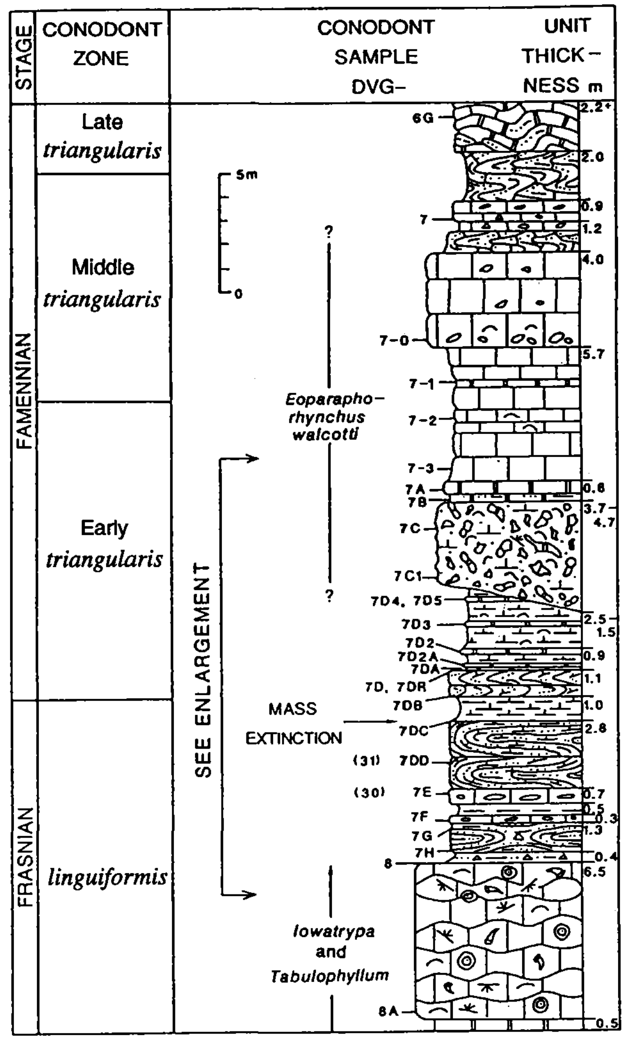


*Figure 14. Detailed stratigraphic section of Upper Devonian slope rocks, 40–79 m below top of Devils Gate Limestone, at Stop 6, Devils Gate, Nevada. Shows position of 27 conodont samples collected across late Frasnian (F/F) mass extinction horizon (Event 10), 1.0 m below Frasnian-Famennian boundary. See enlargement (Fig. 15) for conodont biofacies analysis and sequential subevents related to mass extinction.*

The sequence shown in Figure 14 contains the highest pre-extinction occurrence of the brachiopod *Iowatrypa* and horn coral *Tabulophyllum* and the lowest post-extinction occurrence of the rhynchonellid brachiopod *Eoparaphorhynchus walcotti*. A closeup of the beds across the Frasnian-Famennian (F/F) boundary, shown in Figure 15, shows how the globally recognized subevents of Event 10 are indicated by the rock record. This figure lists percentages of the three most important Late Devonian conodont genera, *Palmatolepis*, *Icriodus*, and *Polygnathus*, and horizontal lines show the positions where the greatest change

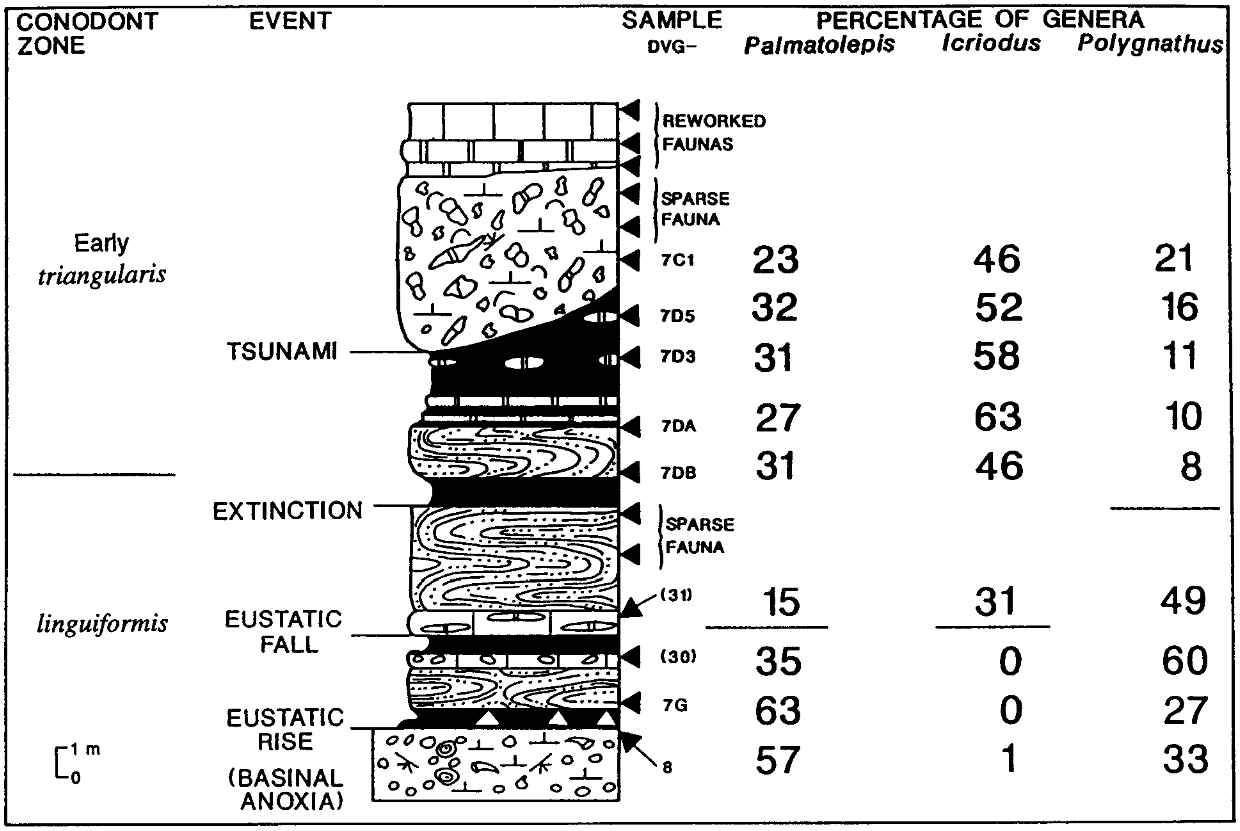


*Figure 15. Enlarged columnar section of Upper Devonian slope rocks, 55–75 m below top of Devils Gate Limestone, at Stop 6, Devils Gate, Nevada. Shows position of representative conodont samples from this interval and percentages of genera in their faunas. Interpretation of sequential subevents related to late Frasnian mass extinction and early Famennian subevent, shown at left of column, are based on lithologic changes and biofacies interpretation of percentages. See Figure 14 for longer columnar section and positions of other relevant conodont samples.*

in abundance of each genus occur in relation to the eustatic fall and the mass extinction at the F/F boundary. Within *Palmatolepis*, all species but one, *Palmatolepis praetriangularis*, became extinct at the top of the *linguiformis* Zone, and new species began to evolve from it within the next younger, Early *triangularis* Zone. Casier et al. (1996) used this same section, originally published by Sandberg et al. (1988), to demonstrate corroborative evidence for an abrupt mass extinction of ostracodes at the same time.

The single most interesting bed within the F/F boundary sequence (Figs. 14, 15) is the thick breccia, interpreted as a tsunamite by Sandberg et al. (1988). This bed is the best preserved and most accessible of similar Early *triangularis* Zone deposits that have been recorded throughout the Northern Hemisphere. Unlike higher and lower debris-flow deposits in the Devils Gate Limestone, this breccia contains abundant clasts of nearshore carbonates throughout and reworked Frasnian conodonts in the turbidite deposited at its top (Fig. 15). It also differs in truncating older beds, whereas other debris flows are essentially bedding concordant. The tsunamite truncates at least 1.5 m of beds in the main section and along strike cuts down below the F/F boundary.

## Coyote Knolls (Stop 7)

Location and access: In T-shaped canyon through low ridge of Devonian rocks, located 5.5 km west of Coyote Knolls and 1 km east of dirt road on west side of Tule Valley, in SW1/4 SW1/4 SW1/4 sec. 35 (unsurveyed), T. 15 S., R. 16 W., Millard Co., Utah, in the Coyote Knolls 1:24,000 quadrangle (lat 39.47°N, long 113.62°W). Section is most easily accessed by turning north from U.S. Highway 6-50, at junction with Utah Highway 159 to south, onto well maintained Gandy dirt road along Nevada-Utah boundary, and then turning east (right) after 12.3 mi at sign marked Knoll Spring onto less used dirt road that is part of old, transcontinental Grand Army of Republic Highway (original Highway 6). This road passes through Cowboy Pass about 31.5 mi from pavement and then descends east

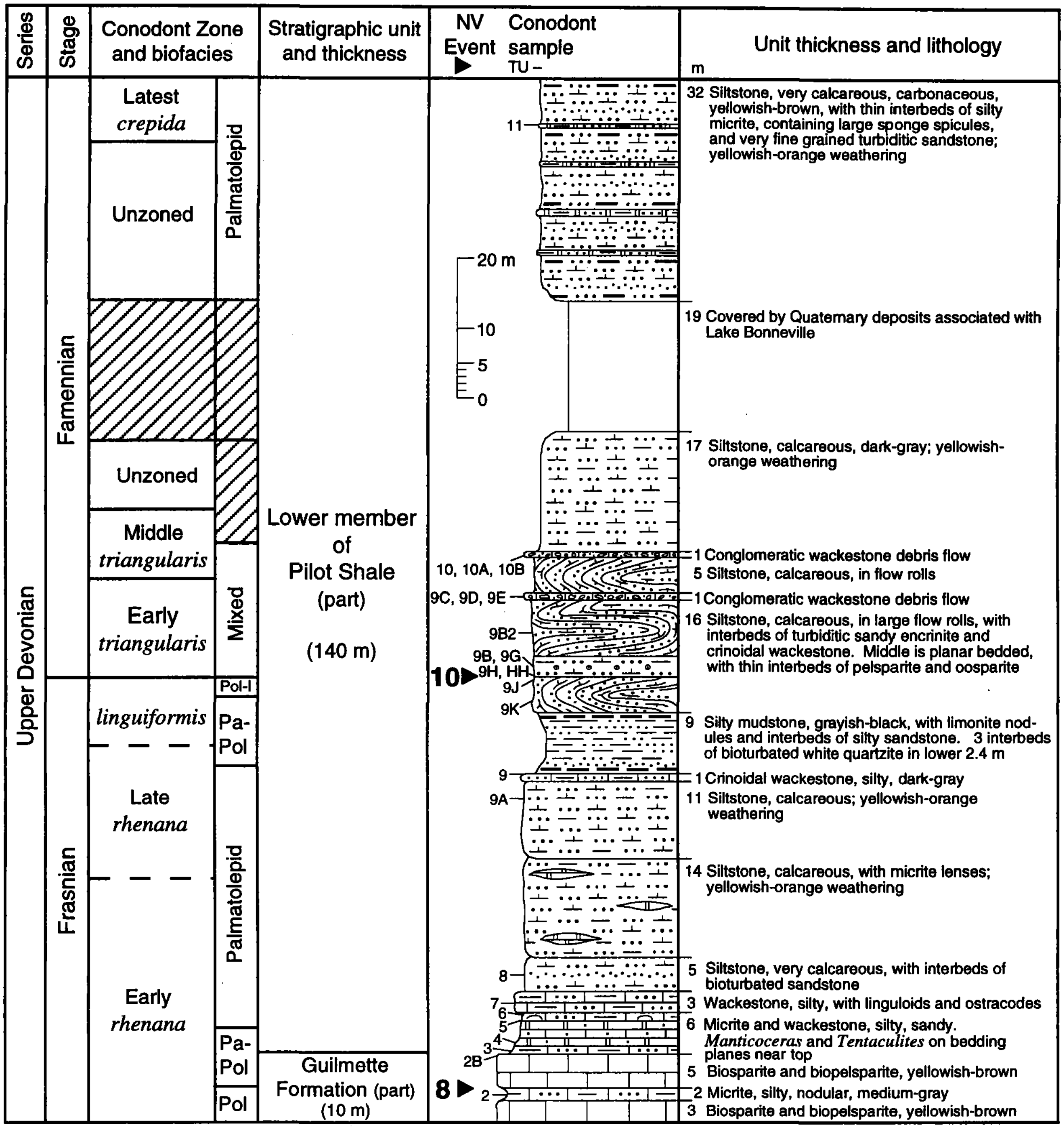


*Figure 16. Stratigraphic section of highest part of Guilmette Formation and lower part of lower member of Pilot Shale on ridge west of Coyote Knolls (Stop 7), Tule Valley, Utah. Section begins on west limb of small anticline near top of Guilmette Formation, so little more of Guilmette is exposed. Event 8, a eustatic deepening, here involves only the top 5 m of the Guilmette and the basal 15 cm of the Pilot and thus locally coincides with eastward extension of the Pilot basin. The position of Event 10, the late Frasnian mass extinction, is here narrowly constrained between two thin (3-cm-thick) calcareous turbidite beds, only 15 cm apart, sampled by TU-9H and TU-9HH. See Figure 17 for detailed closeup of Frasnian-Famennian boundary section.*

slope of Confusion Range. At 4.1 mi east of Cowboy Pass, turn north (left) and drive 9.2 mi on long, straight road trending north-northeast across alluvial fans. Measured section lies below valley floor, but low carbonate knobs at top of ridge are barely visible from road. At this mileage, drive east on faint trail, marked by low stone cairns, across sagebrush-covered flat to edge of hill overlooking carbonate sequence. Park vehicle and descend across Quaternary Lake Bonneville beds into T-shaped canyon.

Discussion: The complete section measured at Stop 7 is shown in Figure 16. Heretofore, only an interpretation of depositional rates and record of conodont dates for this section had been published as part of two Pilot basin models (Sandberg and Poole, 1977; Sandberg et al., 1989). Because of its desert location, most exposures are bare, except where covered by Lake Bonneville deposits, and individual beds can be traced for several hundred meters along strike. The T-shaped canyon is well displayed on the geologic map of the area (Hose, 1963).

Event 8 here involves only the uppermost 5 m of Guilmette Formation and basal 15 cm of overlying Pilot Shale, which both contain the opportunistic but short-lived conodont species *Palmatolepis semichatovae*. This Event here locally coincides with eastward extension of the Pilot basin. Overlying beds of the lower member of the Pilot contain the globally diagnostic early Frasnian coiled ammonoid cephalopod *Manticoceras*, as well as abundant trace fossils studied by Gutschick and Rodriguez (1979). Higher beds of the lower Pilot were deposited on the eastern slope of the Pilot basin and are mostly siltstone turbidites, which shortly after deposition were distorted by soft-sediment deformation into large, recumbent flow rolls.

Flow rolls are most conspicuously displayed, along the left (south) upper arm of the T-shaped canyon, where the detailed section (Fig. 17) across Event 10, the late Frasnian mass extinction was measured. It is difficult to imagine that the Frasnian-Famennian boundary could be precisely located in such a high-energy depositional environment. However, several thin, 1- to 4-cm-thick, encrinitic and calcarenitic turbidites were deposited and have been preserved between the large flow rolls. Fortuitously, two of these thin calcareous turbidites, only 15 cm apart, were deposited just below and just above the Frasnian-Famennian boundary (Fig. 17, samples TU-9HH and TU-9H). As in the similarly constructed closeup section for Devils Gate (Fig. 15), Figure 17 shows the position of the several global subevents associated with Event 10 and the positions where changes in percentages of important conodont genera record the eustatic fall and global mass extinction. For a full discussion of this diagram and similar diagrams of other F/F boundary sections in Europe, see Sandberg et al. (1988).

Above the F/F boundary (Fig. 17), the lower of two thin debris flows, which can be traced for some distance southward from the intersection of the stem and arms of the T-shaped canyon, is dated as having been deposited during the late part of the Early *triangularis* Zone. This timing places it in the same stratigraphic position as the tsunamite at Devils Gate (Fig. 15). Both debris flows contain an abundant shallow-water brachiopod fauna including the diagnostic early Famennian species *Eoparaphorhynchus walcotti*, also present at Stops 4 and 6.

### Little Mile-and-a-Half Canyon (Stop 8)

Location and access: Intersection of Little Mile-and-a-Half Canyon and Ledger Canyon dirt roads is located near the center of sec. 29 (unsurveyed), T. 18 S. R. 16 W., Millard Co., Utah, in the Conger Mountain 1:24,000 quadrangle (lat 39.20°N, long 113.65°W). Main measured section of Pilot Shale, containing position of Event 10, is located 0.3 km northeast of intersection and a few tens of meters west of Ledger Canyon road. Contact between Pilot Shale and underlying Guilmette Formation, containing evidence for Event 8, is best displayed on east side of same road, 0.35 km south of intersection. Events 12, 18, and 20 are located on hill slope extending northwest from intersection to Joana Limestone ridge. Access from Coyote Knolls section (Stop 7) is accomplished by returning to the old Grand Army of Republic road, and turning east (left). Drive 1.7 mi on this road and turn south (right) on Camp Canyon road for 3.4 mi as far as water tank at Skunk Spring. Turn east (left) on road through Joana ridge; drive 0.5 mi and then turn south (right) on Ledger Canyon road in valley formed by Pilot Shale. Drive 5.2 mi to road junction. Four other routes can be used to access Little Mile-and-a-Half Canyon depending on changing, temporary road closures caused by flash floods, which are common in the Confusion Range. The most direct access from U.S. Highway 6 is via the Little Valley road, which passes close to Conger Spring. A detailed map for another field guide (Sandberg et al., 1980) shows this route, as well as locations of the main Pilot section and several other sections that were composited for our complete stratigraphic section (Fig. 18).

Discussion: The composite stratigraphic section of the upper part of the Guilmette Formation, Pilot Shale, and basal beds of the Joana Limestone in and around Little Mile-and-a-Half Canyon is illustrated in Figure 18. This updates earlier versions by Sandberg et al. (1980, fig. 3; 1989, fig. 13), especially for beds enclosing Event 10. A similar columnar section of Mississippian beds from the top of the Joana to the base of the Ely Limestone was shown by Sandberg et al. (1980, fig. 4). The area around Little Mile-and-Half Canyon is shown on a geologic map by Hintze (1974). The relation of the lower Pilot section to

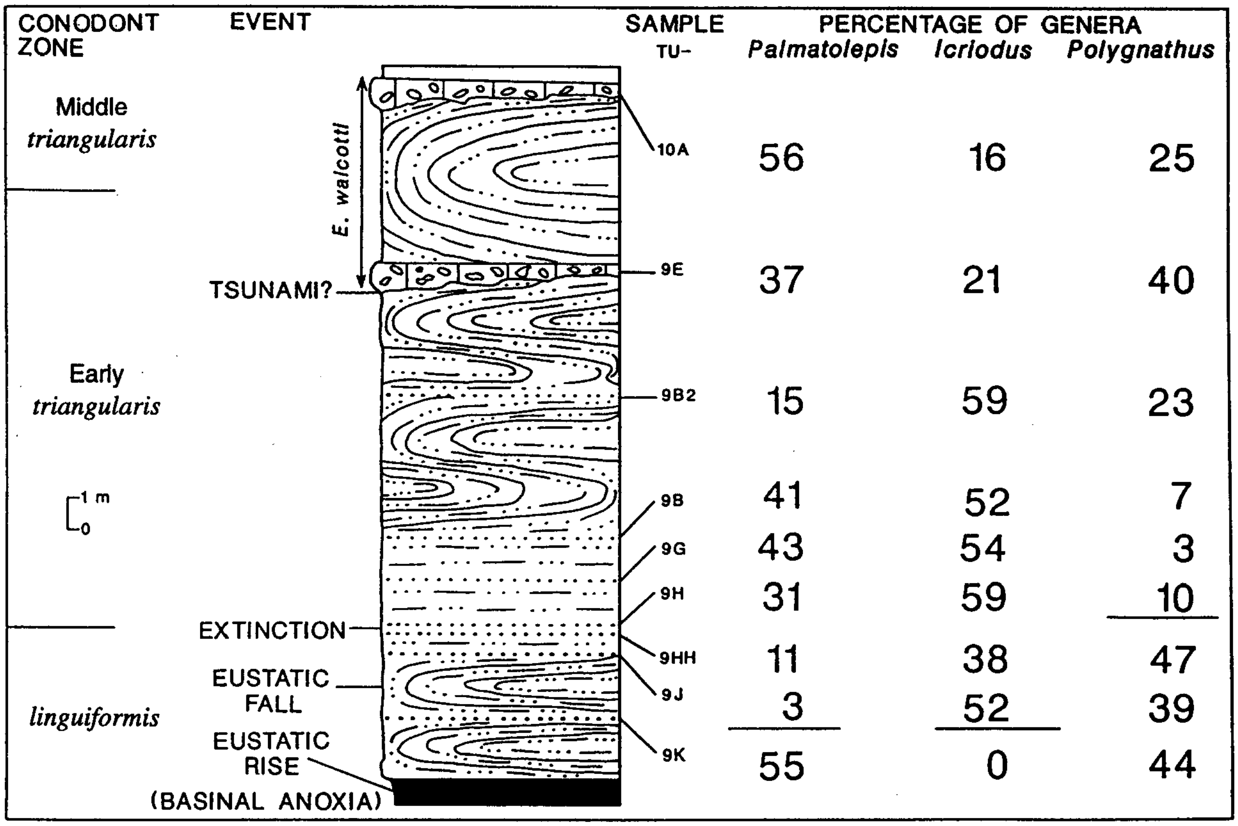


*Figure 17. Enlarged columnar section of Upper Devonian slope rocks, 48–72 m above base of lower member of Pilot Shale, at Stop 7, Coyote Knolls, Utah. Shows position of representative conodont samples from this interval and percentages of genera in their faunas. Interpretation of sequential subevents related to late Frasnian mass extinction and early Famennian subevent, shown at left of column, are based on lithologic changes and biofacies interpretation of percentages. See Figure 16 for longer columnar section and positions of other relevant conodont samples.*

other sections is explained by two Pilot basin models (Sandberg and Poole, 1977, fig. 7; Sandberg et al., 1989, fig. 10).

Although time will not permit a visit by the organized field trip, several Events older than those located in Figure 18 are present or being investigated nearby. Events 1 to 4 are documented in two ridges cut by a canyon heading west from Cattlemens Little Valley, only 4 km northeast of the main Pilot Shale section. In particular, the Fox Mountain Formation, recording Event 1, the Taghanic onlap, is spectacularly displayed in massive limestone cliffs on both sides of an easily accessed, flat-bottomed canyon. This limestone outcrop contrasts sharply with the thin, slope-forming, dolomitic *Stringocephalus*-bearing beds of the upper alternating member of the Simonson Dolostone at the canyon mouth. Down Little Mile-and-a-Half Canyon about 1.5 km from the main Pilot section, a grab sample, supplied to Sandberg by consulting geologists and plotted to originate from the lower part of the Guilmette Formation, contains a deep-water conodont fauna suggestive of either Event 5 or 6. The collection represents a mesotaxid biofacies, unlike the shallow-water pandorinellinid and polygnathid conodont biofacies recovered from other beds of this sequence. We are still searching for the collecting site, which was not accurately located.

Within the main Pilot section (Fig. 18), Event 8 is present in the top 5.5 m of the Guilmette Formation, similarly to its position at Stop 7. Our search for the exact position of Event 10 has narrowed to the lower part of a 12-m interval between the ledge with sample CON-3B3 at its top and a thin calcareous turbidite sampled by CON-3B4 (Fig. 18). This turbiditic siltstone interval is probably identical to the one with large flow rolls enclosing the F/F boundary at Stop 7. However, exposures do not permit recognition of flow rolls here, and so far we have been unable to find any thin calcareous turbidite interbeds. Event 12 is recorded by the resistant conglomeratic turbidite bed capping a low ridge a short distance to the west. Events 18 and 20, as well as intervening Event 19, not shown on Figure 18, are present within two parallel gullies located

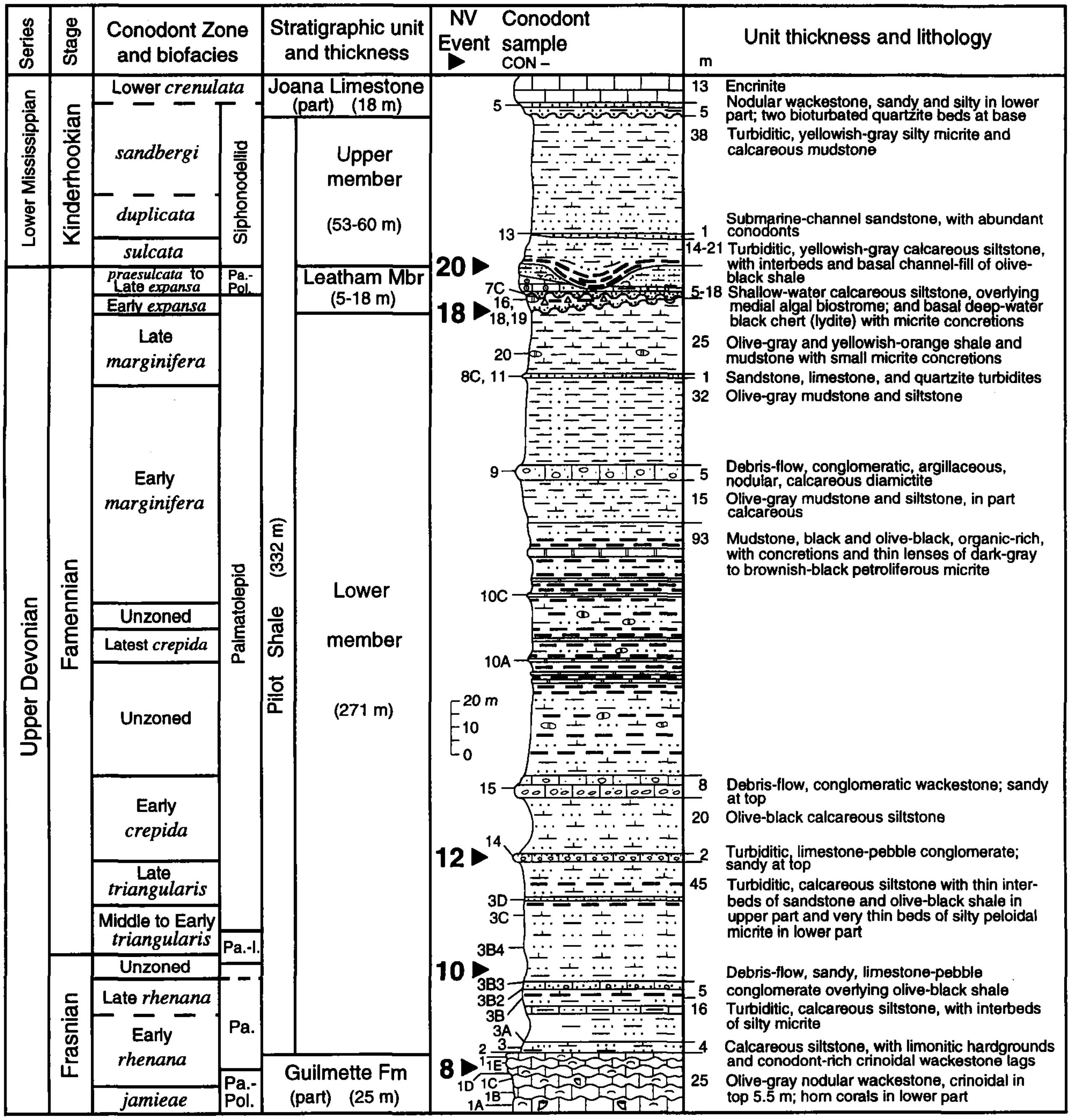


*Figure 18. Composite stratigraphic section of upper part of Guilmette Formation, Pilot Shale, and lower part of Joana Limestone in and around Little Mile-and-a-Half Canyon (Stop 8), Confusion Range, Utah. Updates stratigraphic columns shown by Sandberg et al. (1980, fig. 3; 1989, fig. 13). Event 8, a eustatic deepening, here involves only the top 5.5 m of the Guilmette and thus locally coincides with eastward extension of the Pilot basin. Position of Event 10, the late Frasnian mass extinction, is poorly constrained within siltstone interval because of lack of calcareous turbidite interbeds. Event 18 occurs just above a major continent-wide unconformity, which is here difficult to discern on shale slope without shallow trenching. Event 20 lies at base of a submarine channel that locally truncates part or all of the Leatham Member.*

in the upper part of the Pilot slope to the west, below the cliff-forming Joana Limestone. Event 18 is better displayed near the top of the bare slope below the left gully.

Following Stop 8, the organized field trip will return by the shortest route to paved U.S. Highway 6 and then proceed northeast to Salt Lake City (Fig. 1).

## CONCLUSIONS

The organized field trip has demonstrated that sedimentation in the eastern Great Basin was controlled by a series of eustatic and catastrophic events. Biostratigraphic responses to the eustatic events were described by Johnson and Sandberg (1989). The six major episodes of Famennian eustatic rise in the Northern Hemisphere were interpreted to result from interglacial episodes of Southern Hemisphere glaciation (Sandberg et al., 1988). The glaciation itself was interpreted to have been induced by one or more impacts associated with Event 10. The tsunamite late within the Early *triangularis* Zone at Devils Gate and elsewhere could represent the actual time of impact of one or more extraterrestrial objects, following an episode of cosmic radiation that produced stepwise extinctions and genetic mutants late in the late Frasnian *linguiformis* Zone. These events demonstrate that impacts do have a long-lasting global effect on sedimentation and evolution.

The regional biostratigraphic and sedimentologic responses to the Alamo Impact (Event 6), evidence for which is more spectacular than that for Event 10 in the eastern Great Basin, are now being investigated. If other craters in the eastern and central United States and in Western Europe are parts of a crater chain associated with the Alamo Impact, then biotic responses within the early Frasnian *punctata* Zone should be investigated in these areas. We now believe that the Late Devonian was a time of multiple impacts that should be searched for globally using the Alamo Impact as a paradigm. Such impacts could have produced eustatic rises such as those that drowned the classic Middle Devonian reef tract and two levels of Frasnian reef-and-mudmound tracts in Belgium.

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