# Geodetic Search for Contemporary Fault Creep, Death Valley, 1970-2000

Arthur Gibbs Sylvester, Principal Investigator
Department of Geological Sciences
University of California
Santa Barbara, CA 93106-9630

Final Investigator Report
NPS Permit No. DEVA-2000-018

Date of this Report: 1 March 2001

# *Geodetic Search for Contemporary Fault Creep in Death Valley, 1970-2000*

*By*

Arthur Gibbs Sylvester

Department of Geological Sciences

University of California

Santa Barbara, CA 93106-9630

## ABSTRACT

Repeated leveling across five, presumably active faults in Death Valley and Fish Lake Valley reveals no unequivocal vertical displacement or strain across them in the period between 1970 and 2000. Marginal evidence for about 1 μrad/yr tilting across the north end of the Artist Drive section of the Black Mountains fault zone may be related to nontectonic compaction of basin-fill sediments beneath the faulted alluvial fan or to interseismic tectonic warping due to crustal strain accumulation.

## OBJECTIVE

Five arrays of permanent bench marks were established across five active or potentially active faults in Death Valley and southern Fish Lake Valley to determine, by means of repeated precise leveling, if vertical fault creep is occurring along the faults.

## INTRODUCTION

Youthful fault scarps are abundant and prominent in Death Valley and cause one to wonder "when did the earthquakes happen that produced those scarps?" and "are any of the scarps inexorably growing in height now even without earthquakes?" Other investigators have been seeking the answer to the first question and suspect that the causative earthquakes happened several hundred to several thousands of years ago. This study focuses on the second question by making repeated, infrequent leveling measurements across the scarps during a 30-year period.

Hundreds, thousands, even tens of thousands of years may elapse between earthquakes on a given part of a fault. In fact, nearly continuous slip, as much as 30 mm/yr and termed "interseismic slip" or simply "fault creep", has been documented along only a handful of faults in the world. All but one of the creeping faults are strike-slip faults, including and especially the central portion of the San Andreas fault near Parkfield (e.g., Schulz et al., 1982; Sylvester, 1995; Behr, et al., 1997). The exception is a suspicious case of aseismic normal faulting in the Fish Spring Valley area of western Nevada (Bell and Hoffard, 1990; Bell and Helm, 1998). Whereas fault creep has cogent explanations (e.g., Wesson, 1988), why isn't it more common? Why does it seem to be restricted to strike-slip faults? And, do any faults in Death Valley slip today by means of creep?

Perhaps other faults do creep but time, diligence, and luck are needed to prove it, because the creep displacements may be so small and episodic at times or places that they are simply missed. The San Andreas fault creep (including creep on the Calaveras and Hayward faults) is noteworthy because it is rapid, and consequent damage to engineered structures built on and across the fault is clearly evident (e.g., Steinbrugge, et al., 1960; Rogers and Nason, 1971; Lienkaemper and Galehouse, 1997). Many faults elsewhere in the world pass through vegetated areas, sparsely inhabited areas, or the faults splay into several strands over such a broad zone that the measurement of 1-2 mm/yr is simply tedious and difficult, especially if the creep is vertical. Creep has been measured by several methods (Thatcher, 1986; Sylvester, 1986), but unless the fault is unusually active (such as the San Andreas), most methods yield measurement uncertainties that are about as large as the signal. This dilemma compels one to make either extremely precise measurements over short time periods, or make less-precise measurements over a long time period; a period that is usually much longer than that generally afforded by most research grants or by the careers of even the most diligent investigators.

Recent GPS measurements across the southern Basin and Range Province (Smith et al., 1998; Bennett, et al., 1999; Thatcher, et al, 1999) clearly indicate that right lateral shear strain is occurring across the region at the rate of 12 mm/yr together with 10 mm/yr of E-W extension. Most of this strain is aseismic and concentrated at the west and east margins of the province.

The crustal-strain budget for the region can be balanced only by supposing that some faults slip *interseismically* by creep, at least during the period of the GPS measurements. We commenced a search for a vertical component of missing creep nearly 30 years ago when we placed five arrays of bench marks across oblique-slip faults in Death Valley (fig. 1) that are regarded as active because of

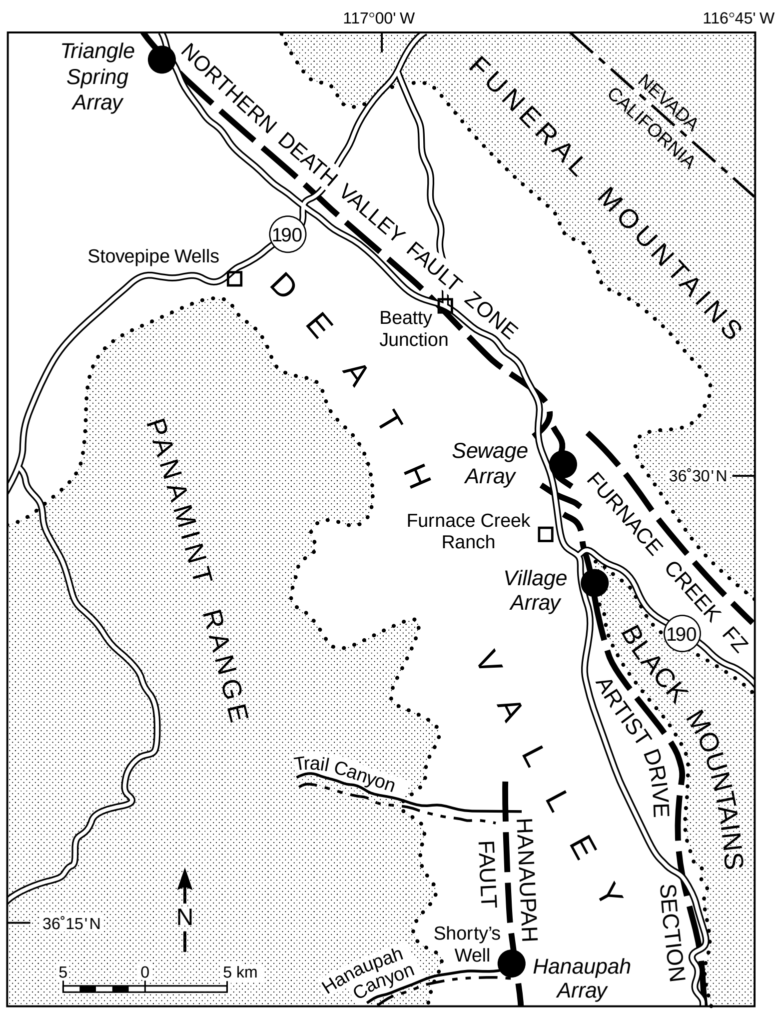



Figure 1. Locations of leveling line arrays in Death Valley, excluding FISH LAKE ARRAY (Nevada).

the youthful scarps along their surface traces. Having now resurveyed these arrays six to ten times, our results as reported herein.

## TECTONIC SETTING

Death Valley, at the west edge of the southern Basin and Range, may be subdivided physiographically into three parts (Burchfiel and Stewart, 1966), each of which owes its modern structural grain to youthful faults. The northern and southern parts trend NNW and contain right-lateral strike-slip fault zones, the Northern Death Valley and the Southern Death Valley, respectively. The central part trends more N-S and is bounded on the east by (from south to north) the Mormon Point, Badwater, and Artist Drive sections of the Black Mountains fault zone, comprising a zone of right-oblique normal-slip faults at the western base of the Black Mountains (Hunt and Mabey, 1966; Wills, 1989; Brogan et al., 1991; Klinger, 1999; Machette, et al., 2001).

The central part of Death Valley is a half-graben inclined eastward toward the Black Mountains and the Black Mountains fault zone. This structural geometry is supported by the eastward tilt of the Badwater saltpan, and by the asymmetry of alluvial-fan size and shape from one side of the valley to the other (Hunt and Mabey, 1966). Additional support comes from gravity data (Hunt and Mabey, 1966; Blakely et al., 1999) and from deep seismic-refraction and reflection profiles (Geist and Brocher, 1987; Serpa et al, 1988; Serpa and Pavlis, 1996). The geophysical data indicate that the valley fill consisting of alluvium, lacustrine, and evaporite deposits is about 3000 m thick, and when combined with geologic data from the Black Mountains, indicate a vertical separation of approximately 5000 m across the Black Mountains fault zone at Badwater.

The type, timing, and amounts of displacement across the Black Mountains fault zone are quite uncertain. Exposures of mullions and slickensides on fresh fault surfaces (e.g., Noble and Wright, 1954; Hill and Troxel, 1966; Miller, 1999) are evidence that it has a significant component of strike-slip. These estimates range from 2 km to 70 km depending on the investigator, the location, and the age of the geologic marker (Slemmons and Brogan, 1999). Northwest horizontal motion of $2.9 \pm 0.6$ mm/yr has been measured between 1993 and 1998 by GPS (Williams et al., 1999), but contemporary vertical displacement has not been measured. At Goblet Canyon, however, about 10 km south of our Village array[1], a vertical displacement rate of 0.9 mm/yr was determined from the 28 m displacement of a rock avalanche that was dated by three cosmogenic exposure ages (Knott, 1998, summarized in Klinger, 1999). Abundant evidence of recent movement on the Black Mountains fault zone is evinced by variably dissected scarps as much as 2 m high on modern alluvium along the Artist Drive section and as high as 10 m along the Badwater and Mormon Point sections (Wills, 1989; Brogan et al., 1991). Klinger and Piety (2001) and Frankel and others (2001) presented evidence for the timing of movement on these sections of the Black Mountains fault zone.

The Southern and Northern Death Valley fault zones, the (pre-Quaternary) Furnace Creek fault zone, and related fault zones in the area are generally regarded as right-slip faults (e.g., Reheis and Sawyer, 1997), but the time and amount of displacement on each are still subjects of investigation. Low, variably dissected, even partially buried scarps, attest to a local component of vertical separation on these faults.

[1] The VILLAGE array is located in a canyon between Breakfast and Golden canyons, a canyon that Knott (2001, p. C91) informally designated as Village Canyon because of the presence of abundant stone rings there of prehistoric age. Prior to 2001, this array was designated as the ARTIST DRIVE array.

The 7-km-long Hanaupah fault is a relatively short, but impressive fault that is due west of Badwater on the western margin of central Death Valley (Hunt and Mabey, 1966; Brogan et al., 1991). It is marked by a prominent, dissected scarp having a maximum height of about 25 m on older upper Pleistocene (Q2) gravel and 2-3 m in younger upper Pleistocene (Q3) gravel (Hunt and Mabey, 1966, p. A103). Evidence of strike-slip is not apparent on this presumably steep, east-dipping normal fault. The height of the older scarp and the degree of erosion indicate that the fault has had several major earthquakes over tens of thousands rather than hundreds or thousands of years, but conclusive information on the fault's slip rate is still lacking.

## METHOD AND PRECISION

In 1969 we placed linear arrays of permanent bench marks (fig. 1) across the Hanaupah fault (HANAUPAH ARRAY), the Artist Drive section of the Black Mountains fault zone (VILLAGE ARRAY), the transition zone between the Northern Death Valley and Black Mountains fault zones (OLD GHOST ARRAY), and the Northern Death Valley fault zone (TRIANGLE SPRINGS ARRAY). Each of these arrays was surveyed in 1970 for the first time. The FISH LAKE ARRAY crosses the Oasis section of the Fish Lake Valley fault zone (Reheis and Sawyer, 1997; Sawyer and Reheis, 1999) in southern Fish Lake Valley. The Fish Lake Valley fault zone (not shown in fig. 1) is the continuation of the Northern Death Valley fault zone into Nevada.

Most of the bench marks in our arrays are Class B rod marks (Floyd, 1978) that penetrate 2-3 m into the ground. Some of the others are 10-cm-long stubs of copper-jacketed, steel weld rod that have been epoxied into 8 cm-deep holes drilled into large, partially buried boulders. The stability of these marks over time is excellent as indicated by the reproducibility of successive resurveys of them (Figs. 3, 4, 5, 6) and by our experience with them in arrays across faults elsewhere in California, Nevada, and Wyoming (e.g., Sylvester, 1995).

The arrays range from 300 m to 430 m in length, with bench marks spaced no more than 25 m apart. Although the short line lengths and the close bench mark spacing were intentional, some arrays were limited by topography. Initially, we hoped to measure displacement right across the surface trace of the fault, so that if interesting height changes were discovered within the first few years of survey, then we would lengthen the array(s) accordingly and do the necessary work to define the nature and width of the strain zone more completely. We did lengthen the eastern end of the VILLAGE ARRAY by 47 m in 1985, because previous surveys indicated that bench mark 544 at the end of the line had risen about 6 mm over 15 years relative to others in the array (Sylvester and Bie, 1986; fig. 2 this study). We also lengthened the east end of the HANAUPAH ARRAY in 1974 by 60 m with two additional bench marks. In all our arrays, bench marks are spaced at less than the maximum permitted for first-order leveling in order to minimize refraction errors (Federal Geodetic Commission, 1984).

We seek to achieve an uncertainty less than or equal to 1 mm x $L^{1/2}$ (where L is the one-way length of the line in kilometers), which is designated as "tectonic first order precision," as compared to "first order precision" of 2 mm x $L^{1/2}$ (Federal Geodetic Commission, 1984). Examples of the precision of these orders of leveling data are given in Table 1.

Table 1. Examples of precision for leveling data.

| L (km) | $L^{1/2}$ (km) | A) Tectonic first order level | B) First order level |
|---|---|---|---|
| 0.100 | 0.32 | 0.32 mm | 0.64 mm |
| 0.500 | 0.71 | 0.71 mm | 1.42 mm |

The majority of our surveys of the Death Valley arrays are "tectonic first order" (Appendix 1). Adverse meteorologic conditions, especially strong wind and heat, are the main factors that generally contributed to surveys having less than "tectonic first order" survey quality. The quality of the March 2000 survey is unusually high, probably because it was done under virtually optimal conditions of gentle breeze and temperatures in the low 80°s F. In addition, VILLAGE and OLD GHOST, the two longest arrays, were surveyed under lightly overcast skies.

The data presented here are uncorrected, observed data. Leveling over such short array lengths with relatively short, balanced sight lengths should be virtually free of systematic errors due to parallax and refraction and, therefore, should not require synthetic corrections (Castle et al., 1994). The close agreement of surveying results for each Death Valley array from one survey to the next justifies this assumption.

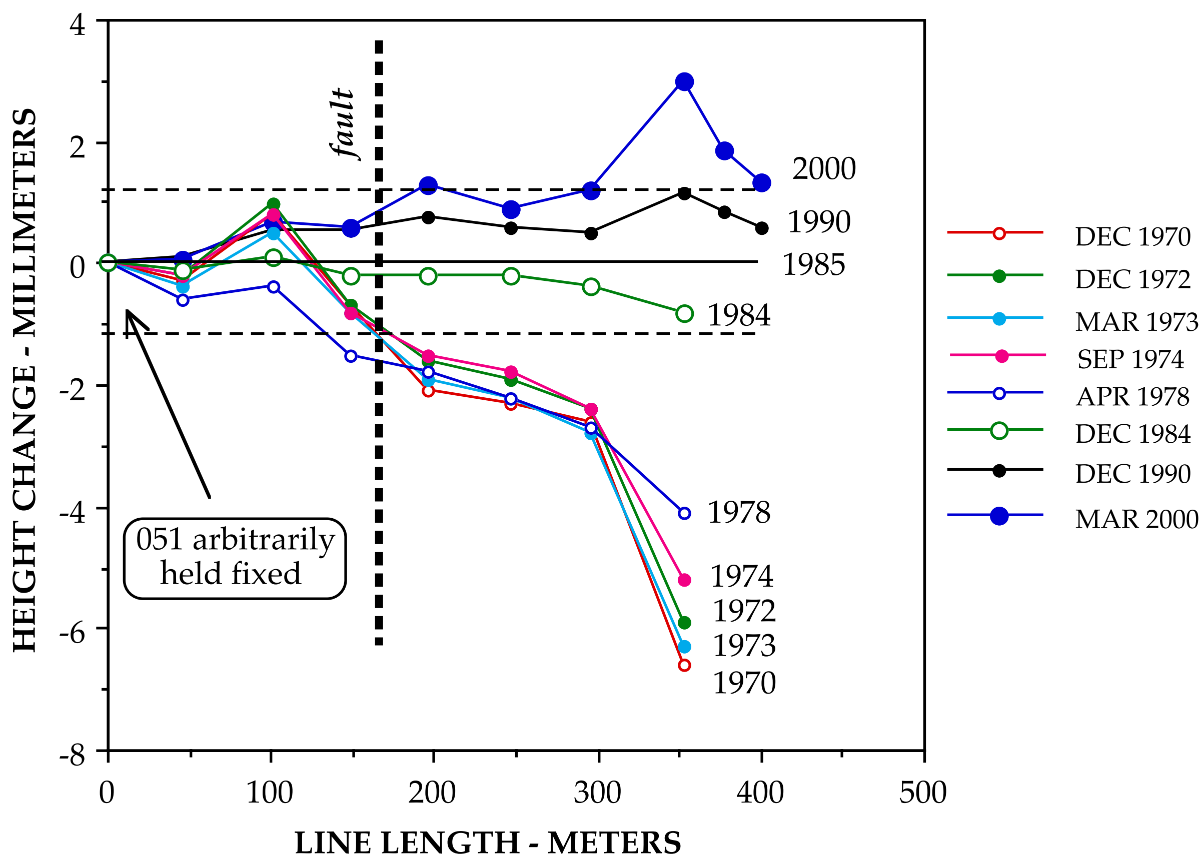



Figure 2. Graph of nine levelings of VILLAGE ARRAY across Artist Drive section of Black Mountains fault zone, 1970 to 2000 relative to 1985 when the array was lengthened. Bench mark 051 is arbitrarily held fixed. One sigma uncertainty in the 1985 survey indicated by parallel dashed lines. Greatest uncertainty is associated with the 1984 survey.

## RESULTS

Changes of bench mark heights are negligible throughout each array, except in the VILLAGE ARRAY, both from bench mark to bench mark, as well as from survey to survey, aside from one or two bench marks that behaved somewhat aberrantly relative to the others. Such slight changes logically lead to the conclusions that the bench marks are stable and that surface displacement has not occurred across the faults, whatever the cause, in the past 30 years. The aberrant bench marks

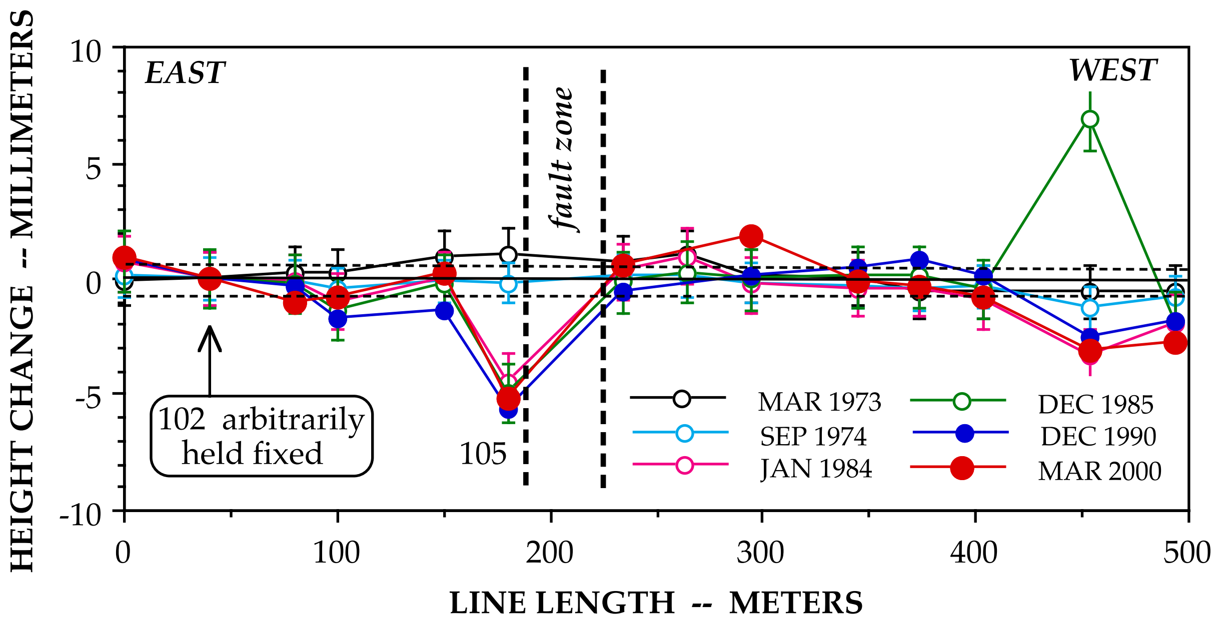



Figure 3. Graph of seven levelings of OLD GHOST ARRAY across fault scarps at Cow Creek, 1971 to 2000. The array is in the transition zone between the Northern Death Valley and Black Mountains fault zones. Bench mark 102 is arbitrarily held fixed. Aberrant bench mark 105 labeled. One sigma uncertainty in 1971 survey indicated by parallel dashed lines.

are clearly evident by having risen or dropped a millimeter or two relative to adjacent bench marks, and then by retaining that height difference throughout the remainder of the surveys (e.g., bench mark 106, fig. 3).

Another such aberrant bench mark is 544 in the east end of the VILLAGE ARRAY (fig. 2), which, rose faster than any of the others between 1970 and 1984. We added two class B rod marks (545 and 546) to the east end of the array to see if perhaps 543 and 544 straddled the trace of a fault undergoing displacement. Since 1985, however, 545 and 546 have risen no faster than 541, 542, and 543, whereas 544 continued to rise somewhat faster, indicating that it is relatively unstable (fig. 2).

The resurveys of the VILLAGE ARRAY indicate that height changes among all bench marks were less than 1 mm between 1970 and 1978. Between 1978 and 1984, however, the east end of the line rose 5 mm, and between 1985 and 2000 it rose an additional millimeter (fig. 2). The pattern of the height changes among all the bench marks indicates that the line tilted about 11 µrad westward, valleydown, over a period of 11 years between 1974 and 1985. Qualitative integration of the bench mark heights from 1978 to 2000 suggests that the tilt was relatively continuous at a rate of 1 µrad/yr. The uncertainties attached to several of the relevant surveys are as great as the height changes themselves (fig. 2), however, so the signal may be perceived as being not statistically significant, and a conclusion of tilting is only permissive rather than compelling.

Significant height changes among bench marks or across faults are not evident in the OLD GHOST (fig. 3), TRIANGLE (fig. 4), or FISH LAKE (fig. 5) arrays during the period of study.

A case can be made for minor displacement across the Hanaupah fault between 1974 and 1990 (fig. 6B). The first survey of this array was done in 1970, but a comparison with subsequent surveys is not especially revealing (fig. 6A). The line was lengthened 60 m for the 1974 survey. Only in the 1990 and 2000 surveys were the new 1974 bench marks surveyed. A comparison of these surveys (1970, 1990, and 2000) reveals that the footwall block subsided about one millimeter

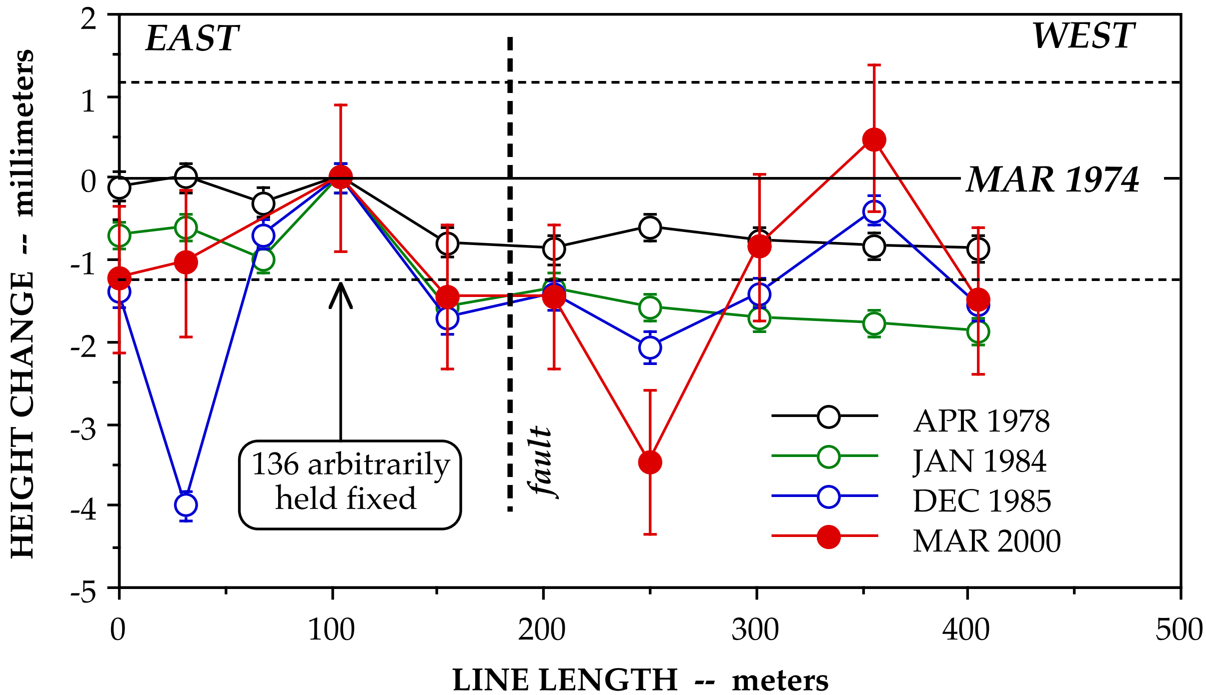



Figure 4. Graph of five levelings of TRIANGLE SPRING ARRAY across Northern Death Valley fault, 1974 to 2000. Bench mark 136 is arbitrarily held fixed. One sigma uncertainty in 1974 survey indicated by parallel dashed lines.

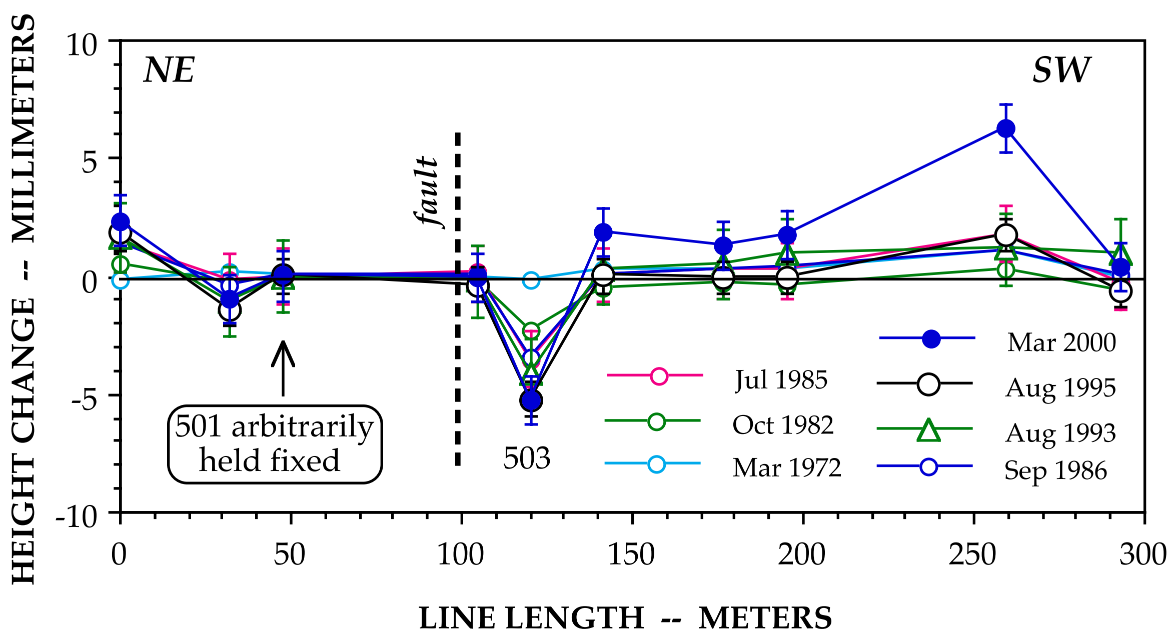
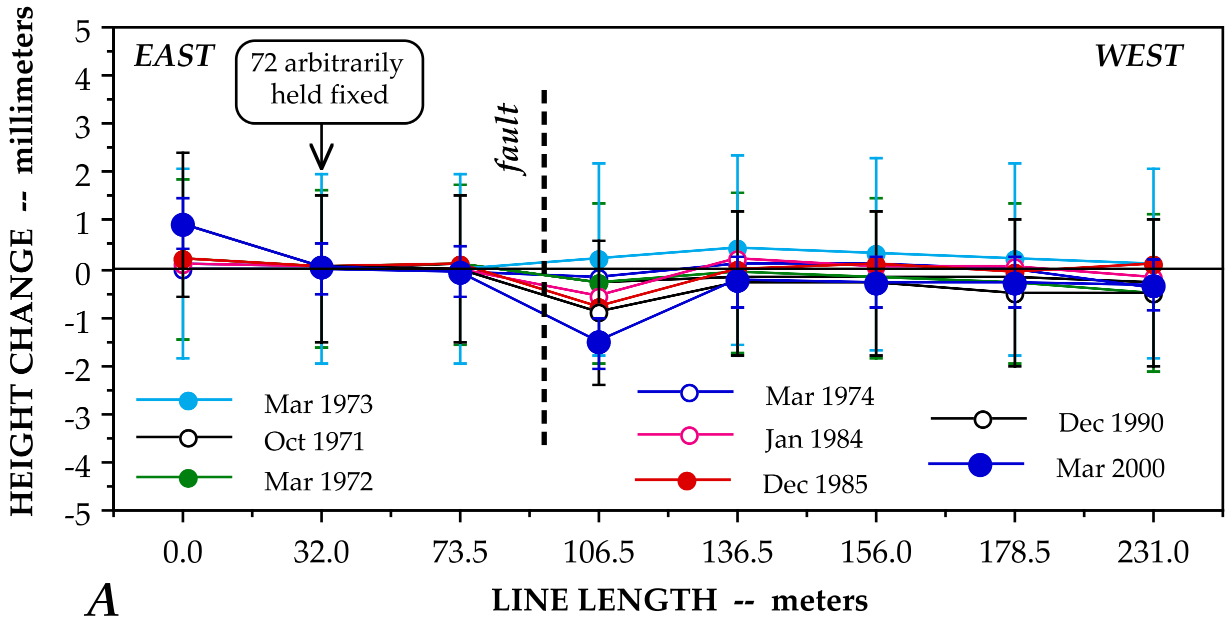



Figure 5. Graph of eight levelings of FISH LAKE ARRAY across Fish Lake Valley fault near Oasis, 1971 to 2000. Bench mark 501 is arbitrarily held fixed. Aberrant bench mark 503 labelled. One sigma uncertainty of 0.2 mm in 1971 survey is too small to indicate on graph.



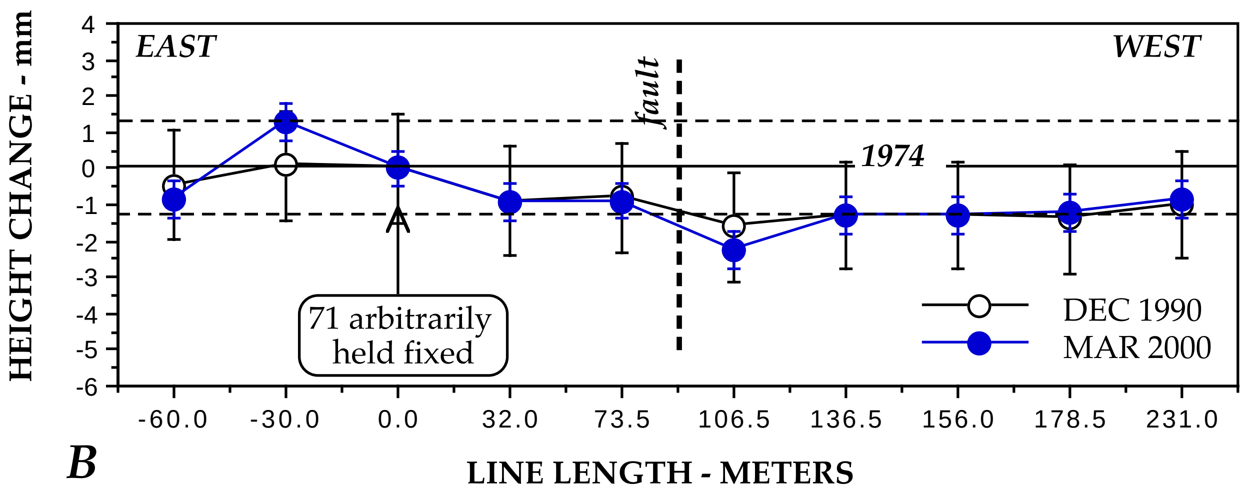




Figure 6. Graphs of repeated levelings of HANAUPAH ARRAY across the Hanuapah fault. A) Nine surveys, October 1970 to March 2000. Bench mark 72 is arbitrarily held fixed. B) Three surveys, 1974, 1990, 2000. Bench mark 71 is arbitrarily held fixed. One sigma uncertainty in 1974 survey indicated by parallel dashed lines.

between 1974 and 1990, but the change is within the uncertainty of all three surveys, so the height change across the fault is not statistically meaningful.

## DISCUSSION

Our search for vertical creep was initially directed to only a few of several faults in the western part of the Basin and Range Province that have been recently active, judging from the youthfulness of their scarps. Such faults include those in Owens Valley (Beanland and Clark, 1994), Deep Springs Valley (Bryant, 1989; Lee et al., 1996; Reheis and Sawyer, 1997), Death Valley (Brogan et al., 1991; Klinger and Piety, 1996), Fish Lake Valley (Reheis and Sawyer, 1997), Carson and Eagle valleys (Nevada) (Lawson, 1912), Fish Spring Flat (Nevada) (Bell and Hoffard, 1990; Bell and Helm, 1998), and those associated with historic earthquakes in the Central Nevada Seismic Belt (Pleasant Valley 1915, Cedar Mountain 1934, and Dixie Valley-Fairview Peak, 1954). But if the return frequency of these earthquakes is on the order of thousands to tens of thousands of years in this region as paleoseismic studies suggest (see Frankel, et al., 2001; ), then we should have focused on older faults having greatly degraded scarps if we hoped to record their interseismic activity within our lifetime. Because our sampling of interseismic activity is so limited in time and space, it is hazardous to extrapolate the results to the entire Basin and Range, therefore, and the following discussion should be so regarded.

The surveys reported here focus on three faults in Death Valley and one in Fish Lake Valley to the north. The Death Valley faults include one crossing each of the Hanaupah fault, Artist Drive section of the Black Mountains fault zone, and transition zone between the Black Mountains and Northern Death Valley fault zones. We report on two widely spaced crossings of the Northern Death Valley and Fish Lake Valley fault zone. If any one of the surveys had revealed suspicious behavior that could be sensibly linked to tectonic activity, then we would have lengthened the lines, increased the frequency of the surveys, and probably sought NPS permission to establish additional fault crossing arrays. With the exception of the VILLAGE ARRAY, however, we did not observe any such activity in our 30 years of observation and, thus, conclude from our limited sampling that the surface traces of those faults were inactive in that time.

The VILLAGE surveys may evince tilt within a broad zone of tectonic warping across the faults of the Artist Drive section rather than discrete slip along any single fault plane; this warping may be related to tectonism or nontectonic compaction of the basin fill, or to both processes. If it were nontectonic, one might expect the compaction to be a continuous phenomenon rather than episodic. A much longer array and much more time would be required to determine whether the observed tilt is tectonic or nontectonic. A longer line would be difficult to establish, especially across the Badwater playa and up the steep front of the Black Mountains. The postulated tilt is so small that an exceptionally long time will be required for its confirmation by GPS methods, given their current ±5 mm vertical uncertainty.

A primary objective of this project is to reconcile the GPS observations of 12 mm/yr right shear and 10 mm/yr extension in the western Basin and Range with the lack of creep on Death Valley faults. That can be done qualitatively and inconclusively by supposing that Death Valley faults do not creep interseismically and so are not contributors to contemporary regional strain as measured geodetically. However, it is more likely that the shear is so episodic on any given fault that 30 years is an insufficient length of time to measure any consequent creep, or 1) that the shear is purely horizontal and our vertical measurements are insensitive to the regional deformation, or 2) that our arrays are imperfectly located to measure creep in Death Valley, or 3) that the geodetic data provided here may constitute permissive evidence for continuing major elastic strain accumulation in the brittle crust, possibly on one or all of the faults that we have been monitoring. It is also possible that contemporary strain is apportioned across so many faults that the Death Valley faults contribute only a fraction of the total creep which is too small for us to measure in 30 years. Future surveys of the arrays *may* tell the answer and the next earthquake in the region *will* tell.

The lack of significant displacement in our VILLAGE ARRAY compared to the observed long-term slip rate of 0.9 mm/yr at Goblet Canyon (Knott, 1998 in Klinger, 1999) just 10 km south of the VILLAGE ARRAY, is perhaps the best reason to argue that displacement on the Black Mountains fault zone probably occurs only at the times of large earthquakes, and that the Black Mountains fault zone – and by extrapolation, all other Basin and Range normal faults – does not creep interseismically, at least at the surface.

## CONCLUSIONS

Repeated leveling across ostensibly active faults in the central part of Death Valley and southern part of Fish Lake Valley over a 30 year period indicates that vertical near-field strain has not taken place across the Hanaupah fault and Northern Death Valley fault zone, but the leveling does provide marginal evidence of about 1 μrad/yr interseismic tilting associated with the Artist Drive section of the Black Mountains fault zone. That conclusion is tenuous because the magnitude of the apparent signal is about the same as that of the noise inherent in the leveling method. The inferred tilt may be related just as easily to nontectonic compaction of basin-fill sediments beneath the faulted alluvial fan as it can be to tectonic warping.

## ACKNOWLEDGMENTS

The 2000 survey was supported by a grant from the UCSB Academic Senat, and fieldwork was done with the help of Eric Cline, Jeff Marsh, Brett Wanner, and David Zell. Prior surveys were supported by University of California President's Undergraduate Research Fund grants to UCSB undergraduate students Tom Foster, Rick Keller, John Byrd, Scott Bie, and Gerald Bawden. I am grateful to these intrepid students and their helpers for their work on this project. Pete Sanchez and Richard L. Anderson in the NPS Resources Management Division of Death Valley National Park greased the bureaucratic skids that permitted this long-term project to transpire. Robert O. Castle kindly reviewed and returned the manuscript the same day he received it. Dottie McLaren drafted the maps, and Lee-Ann Bradley (USGS) updated the graphs in this paper.

## REFERENCES CITED


Beanland, S., and Clark, M.M., 1994, The Owens Valley fault zone, eastern California, and surface faulting associated with the 1872 earthquake: U.S. Geological Survey Bulletin 1982, 29 p.

Behr, J., Bilham, R., Bodin, P., Breckenridge, K., and Sylvester A.G., 1997, Increased surface creep rates on the San Andreas fault southeast of the Loma Prieta mainshock (p. D179-D192), *in* Reasonberg, P.A., ed., Loma Prieta, California, Earthquake of October 17, 1989—Aftershocks and Postseismic Effects: U.S. Geological Survey Professional Paper 1550-D, 312 p.

Bell, J.W., and Hoffard, J.L., 1990, Late Quaternary tectonic setting for a possible fault creep event in the Pine Nut Mountains area, western Nevada: Geological Society of America Abstracts with Programs, v. 22, no. 3, p. 7.

Bell, J.W., and Helm, D.C., 1998, Ground cracks on Quaternary faults in Nevada: Hydraulic and tectonic (p. 165-173), *in* Borchers, J.W., ed., Land Subsidence Case Studies and Current Research—Proceedings of the Dr. Joseph F. Poland Symposium: Association of Engineering Geologist Special Publication No. 8, 576 p.

Bennett, R.A., Davis, J.L., and Wernicke, B.P., 1999, Present-day pattern of Cordilleran deformation in the western United States: Geology, v. 27, p. 371-374.

Blakely, R.J., Jachens, R.C., Calzia, J.P., and Langenheim, V.E., 1999, Cenozoic basins of the Death Valley extended terrane as reflected in regional-scale gravity anomalies (p. 1-16), *in* Wright, L.A., and B.W. Troxel, eds., Cenozoic Basins of the Death Valley Region: Geological Society of America Special Paper 333, 381 p.

Brogan, G.E., Kellogg, K.S., Slemmons, D.B., and Terhune C.L., 1991, Late Quaternary faulting along the Death Valley-Furnace Creek fault system, California and Nevada: U.S. Geological Survey Bulletin 1991, 23 p.

Bryant, W.A., 1989, Deep Springs fault, Inyo Country, California—An example of the use of relative-dating techniques: California Geology, v. 42, p. 243-255.

Burchfiel, B.C., and Stewart, J. H., 1966, “Pull-apart” origins of the central segment of Death Valley, California: Geological Society of America Bulletin, v. 77, p. 439-442.

Castle, R.O., Mark, R.K., and Shaw, R.H., 1994, An empirical assessment of refraction error in leveling as a function of survey order and environment: U.S. Geological Survey Bulletin 2114, 50 p.

Federal Geodetic Commission, 1984, Standards and specifications for geodetic control networks: Rockville, MD, National Geodetic Survey, 31 p.

Floyd, R.P., 1978, Geodetic bench marks: Washington, D.C., National Oceanic and Atmospheric Administration Manual NOS NGT 1, 31 p.

Frankel, K. L., Jayko, A. S., and Glazner, A. F., 2001, Characteristics of Holocene fault scarp morphology, southern part of the Black Mountains fault zone, Death Valley, Chap. M, pp. M205-213, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

Geist, E.L., and Brocher, T.M., 1987, Geometry and subsurface lithology of southern Death Valley basin, California, based on refraction analysis of multichannel seismic data: Geology, v. 15, p. 1159-1162.

Hill, M.L., and Troxel, B.W., 1966, Tectonics of Death Valley region, California: Geological Society of America Bulletin, v. 77, p. 435-438.

Hunt, C.B., and Mabey, D.R., 1966, Stratigraphy and structure, Death Valley, California: U.S. Geological Survey Professional Paper 494-A, 162 p.

Klinger, R.E., 1999, Tectonic geomorphology along the Death Valley fault system—Evidence for recurrent Late Quaternary activity in Death Valley National Park (p. 132-140), *in* Slate, J.P., ed., Proceedings of Conference on Status of Geologic Research and Mapping, Death Valley National Park. U.S. Geological Survey Open-File Report 99-153, 177 p.

Klinger, R.E., and Piety, L.A., 1996, Final Report—Evaluation and Characterization of Quaternary faulting on the Death Valley and Furnace Creek faults, Death Valley, California: Yucca Mountain Project, Activity 8.3.1.17.4.3.2: Denver, CO, Bureau of Reclamation Seismotectonic Report 96-10, prepared for the U.S. Geological Survey in cooperation with the U.S. Department of Energy, 98 p.

Klinger, R. E., and Piety, L.A., 2001, Holocene fault and slip rates along the Black Mountains fault zone near Mormon Point, Chap. L, pp. L193-204, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

Knott, J.R., 1998, Late Cenozoic tephrochronology, stratigraphy, geomorphology, and neotectonics of the western Black Mountains piedmont, Death Valley, California—Implications for the spatial and temporal evolution of the Death Valley fault zone: Riverside, University of California, unpublished Ph.D. dissertation, 407 p.

Knott, J. R., 2001, Field trip guide for Day C, central Death Valley, Chap. C, pp. C89-116, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

Lawson, A.C., 1912, The recent fault scarps at Genoa, Nevada: Seismological Society of America Bulletin, v. 2, p. 193-200.

Lee, J., Rubin, C., Austin, K., Blanton, W., Cadena, A., Johnson, E., and Gans P., 1996, Quaternary faulting along the Deep Springs fault, California: EOS [Transactions of American Geophysical Union], v. 77, p. F461.

Lienkaemper, J.J., and Galehouse, J.S., 1997, Revised long-term creep rates on the Hayward Fault, Alameda and Contra Costa counties, California: U. S. Geological Survey Open-File Report 97-0690, 18 p.

Machette, M. N., Klinger, R. E., J. R. Knott, Wills, C. J., Bryant, W. A., and Reheis, M. C., 2001. A proposed nomenclature for the Death Valley fault system, Chap. J., pp. J173-183, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological

Survey Open-File Report 01-51, 246 p.

Miller, M.G., 1999, Gravitational reactivation of an extensional fault system, Badwater Turtleback, Death Valley, California (p. 367-376), *in* Wright, L.A., and B.W. Troxel, eds., Cenozoic Basins of the Death Valley Region: Geological Society of America Special Paper 333, 381 p.

Noble, L.F., and Wright, L.A., 1954, Chapter II — Geology of central and southern Death Valley region, California (p. 143-160), *in* Jahns, R. H., ed., Geology of Southern California: California Division of Mines Bulletin 170, 160 p.

Reheis, M.C., and Sawyer, T.L. , 1997, Late Cenozoic history and slip rates for the Fish Lake Valley, Emigrant Peak, and Deep Springs fault zones, Nevada and California: Geological Society of America Bulletin, v. 109, p. 280-299.

Rogers, T.H., and Nason, R.D., 1971, Active fault displacement on the Calaveras fault zone at Hollister, California: Seismological Society of America Bulletin, v. 61, p. 399-416.

Sawyer, T.L., and Reheis, M.C., 1999, Seismic potential of the Fish Lake Valley fault zone, Nevada and California (p. 150-151), *in* Slate, J.P., ed., Proceedings of Conference on Status of Geologic Research and Mapping, Death Valley National Park: U.S. Geological Survey Open-File Report 99-153, 177 p.

Schulz, S.S., Mavko, G.M., Burford, R.O., and Stuart, W.D., 1982, Long-term fault creep observations in central California: Journal of Geophysical Research, v. 87, p. 6977-6982.

Serpa, L., and six others, 1988, Structure of the central Death Valley pull-apart basin and vicinity from COCORP profiles in the southern Great Basin: Geological Society of America Bulletin, v. 100, p. 1437-1450.

Serpa, L., and Pavlis, T. L., 1996, Three-dimensional model of the late Cenozoic history of the Death Valley region, southeastern California: Tectonics, v. 15, no. 6, p. 1113-1128.

Slemmons, D.B., and Brogan, G.E., 1999, Quaternary strike-slip components of the Death Valley fault between the Furnace Creek and southern Death Valley fault zones (p. 152-153), *in* Slate, J.P., ed., Proceedings of Conference on Status of Geologic Research and Mapping, Death Valley National Park: U.S. Geological Survey Open-File Report 99-153, 177 p.

Smith, R.B., Meertens, C.M., and Martinez, L.J., 1998, Implications of GPS deformation measurements on earthquake hazard assessment of the Wasatch fault zone: Seismological Research Letters, v. 69, no. 2, p. 141.

Steinbrugge, K.V., Zacher, E.G., Tocher, D., Whitten, C.A., and Clair, C.N., 1960, Creep on the San Andreas fault: Seismological Society of America Bulletin, v. 50, p. 396-404.

Sylvester, A.G., 1986, Near-Field Tectonic Geodesy, Chapter 11, *in* Wallace, R.E., ed., Active Tectonics: National Academy Press, Washington, D.C., 266 p.

Sylvester, A.G., 1995, Nearfield vertical displacement in the creeping segment of the San Andreas fault, central California, 1975 to 1994: Tectonophysics, v. 247, p. 25-47.

Sylvester, A.G., and Bie, S.W., 1986, Geodetic monitoring of fault movements in Death Valley, 1970-1985 (p. 41-44), *in* Troxel, B. W., ed., Quaternary Tectonics of Southern Death Valley: Pacific Cell Friends of the Pleistocene Field Guidebook, 44 p.

Sylvester, A. G., 2001, Search for contemporary fault creep, Death Valley, 1970-2000, Chap. N, pp. M205-213, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late

Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

Thatcher, W., 1986, Geodetic measurement of active tectonic processes, Chapter 10, *in* Wallace, R. E., ed., Active Tectonics: National Academy Press, Washington, D.C., 266 p.

Thatcher, W., Foulger, G.R., Julian, B.R., Quilty, E, and Bawden, G.W., 1999, Present-day deformation across the Basin and Range province, western United States: Science, v. 283, p. 1714-1718.

Wesson, R.L., 1988, Dynamics of fault creep: Journal of Geophysical Research, v. 93, p. 8929-8951.

Williams, T.B., Johnson, D.J., Miller, M.M., and Dixon, T.H., 1999, GPS-determined constraints on interseismic deformation along active fault zones with the Death Valley region, southeastern California (p. 149), *in* Slate, J.P., ed., Proceedings of Conference on Status of Geologic Research and Mapping, Death Valley National Park: U.S. Geological Survey Open-File Report 99-153, 177 p.

Wills, C.J., 1989, A neotectonic tour of the Death Valley fault zone: California Geology, v. 42, p. 195-200.

Wright, L.A., and Troxel, B.W., 1967, Limitations on right-lateral, strike-slip displacement, Death Valley and Furnace Creek fault zones, California: Geological Society of America Bulletin, v. 78, p. 933-950.

Wright, L.A., and Troxel, B.W., 1984, Geology of the north-half Confidence Hills quadrangle, Inyo County, California: California Division of Mines and Geology Map Sheet 34.

# APPENDIX 1

Location, Site Maps, Dates of Surveys and Closures, Survey Data
for UCSB Leveling Lines in Death Valley

arranged from North to South

## FISH LAKE VALLEY Level Line Location Information

**Latitude:** 37°24’28" **Length:** 275.0m
**Longitude:** 117°51’47" **Number of Bench marks:** 10

**Date of Initial Survey:** 30 September 1971 **Number of Surveys to 2001:** 10
**Date of Latest Survey:** 28 March 2000

**Trespass Permission:** None needed, but the line does lie within a Wilderness Area, so that vehicles cannot drive closer than 200 m of the first bench mark.

**Directions:**
This line crosses the Furnace Creek fault on the west side of Fish Lake Valley, 4 miles SSW of the Esmeralda, Mono, and Inyo counties intersection. The level line is located near an unnamed access road 0.8 mile south of the windmill on Eureka Valley Road in Fish Lake Valley. It begins at monument 500, marked by a short wooden stake near a small wash 10 m north of the access road, and it extends across the alluvial fan on the west side the valley.

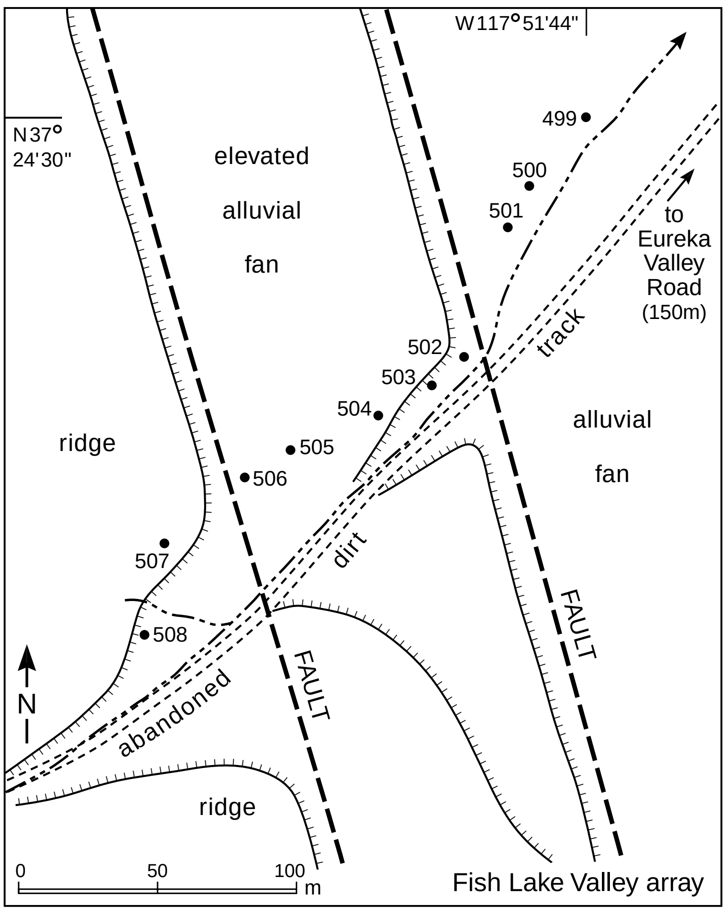
**Comments:**
The line has been surveyed several times following earthquakes in the Bishop and Mammoth areas to determine if these earthquakes triggered vertical displacement on the Furnace Creek fault. The most recent surveys are plotted in an accompanying diagram and have such small variations in bench mark heights, that one may conclude that earthquakes to 1986 had no vertical effect on the fault, especially after the Chalfant Valley earthquake (M 6.2) of 21 July 1986, 50 km west-northwest of the array (Sylvester, 1989). Levelings from 1971 to 2000 indicate that no displacement has occurred across the fault (Sylvester, 2001).

**References:**
Sylvester, A. G., 1989. Triggered vertical strain across active strike-slip faults in southern California. Abstracts Volume, 28th International Geological Congress, Washington, D. C., v. 3, 207-208.

Sylvester, A. G., 2001. Search for contemporary fault creep, Death Valley, 1970-2000, Chap. N, pp. M205-213, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

## • FISH LAKE Leveling Line Surveying Data

| SURVEY DATE | PRECISION (ppm) | CLOSURE (cm) | SURVEY ORDER |
|---|---|---|---|
| 30 September 1971 | 0.023 | -0.001 | Tectonic 1 st |
| 19 March 1972 | 0.164 | -0.004 | Tectonic 1 st |
| 26 March 1973 | 2.584 | 0.071 | First |
| 02 July 1981 | 0.182 | 0.005 | Tectonic 1 st |
| 02 October 1982 | 0.076 | 0.002 | Tectonic 1 st |
| 07 July 1985 | 1.181 | 0.032 | Tectonic 1 st |
| 06 September 1986 | 0.182 | -0.005 | Tectonic 1 st |
| 20 August 1993 | 1.527 | -0.042 | Tectonic 1 st |
| 29 August 1995 | 0.691 | 0.019 | Tectonic 1 st |
| 28 March 2000 | 1.0239 | -0.030 | Tectonic 1 st |




Site map of FISH LAKE leveling array across Oasis segment of Fish Lake Valley fault zone, southern Fish Lake Valley.

## FISH LAKE VALLEY Leveling Data 1970 to 2000

| BENCH MARK | DISTANCE | 30-Sep-71 | 19-Mar-72 | 26-Mar-73 | 21-Jul-81 | 2-Oct-82 | 7-Jul-85 | 6-Sep-86 | 20-Aug-93 | 19-Aug-95 | 28-Mar-00 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 499 | 0.0 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 |
| 500 | 32.0 | 12.36880 | 12.36914 | 12.36960 | 12.36797 | 12.36790 | 12.36723 | 12.36706 | 12.36609 | 12.36559 | 12.36546 |
| 501 | 48.0 | 13.49128 | 13.49144 | 13.49208 | 13.49075 | 13.49060 | 13.48992 | 13.48988 | 13.48962 | 13.48946 | 13.48892 |
| 502 | 104.5 | 17.59430 | 17.59440 | 17.59470 | 17.59360 | 17.59360 | 17.59310 | 17.59300 | 17.59244 | 17.59212 | 17.59191 |
| 503 | 120.5 | 19.73480 | 19.73480 | 19.73510 | 19.73190 | 19.73200 | 19.72990 | 19.72990 | 19.72901 | 19.72778 | 19.72719 |
| 504 | 141.5 | 22.59280 | 22.59320 | 22.59450 | 22.59180 | 22.59160 | 22.59150 | 22.59150 | 22.59146 | 22.59099 | 22.59230 |
| 505 | 176.5 | 25.52370 | 25.52410 | 25.52630 | 25.52290 | 25.52290 | 25.52260 | 25.52260 | 25.52256 | 25.52181 | 25.52263 |
| 506 | 195.5 | 27.04450 | 27.04490 | 27.04580 | 27.04360 | 27.04350 | 27.04340 | 27.04350 | 27.04378 | 27.04261 | 27.04392 |
| 507 | 259.3 | 33.45630 | 33.45750 | 33.46480 | 33.45610 | 33.45580 | 33.45670 | 33.45600 | 33.45579 | 33.45622 | 33.46022 |
| 508 | 293.3 | 33.87880 | 33.87890 | 33.87900 | 33.87760 | 33.87780 | 33.87720 | 33.87750 | 33.87808 | 33.87641 | 33.87680 |

## TRIANGLE SPRING Level Line (Line 130)

**Latitude:** 36°42’40" **Length:** 409.4m
**Longitude:** 117°07’20" **Number of Bench marks:** 10

**Date of Initial Survey:** 1 October 1970 **Number of Surveys to 2001:** 10
**Date of Latest Survey:** 26 March 2000

**Trespass Permission:** Superintendent
National Park Service
Death Valley National Park
Death Valley, CA 92328

**Directions:**
The level line begins 7.1 miles north of the junction where Highway 190 splits into Hwy 190 North and Hwy 190 South. Vehicles must not be driven off the shoulder of the paved road without the expressed and written permission of the Superintendent.

**Comments:**
This line constitutes one leg of the four legs of a strain quadrilateral at this site across the Furnace Creek fault on the east side of Death Valley, three miles northwest of Stovepipe Wells.

**Results:**
Observed changes are less than the standard deviation of the allowable error during the 30 year history of its surveys (Sylvester and Bie, 1986; Sylvester, 2001).

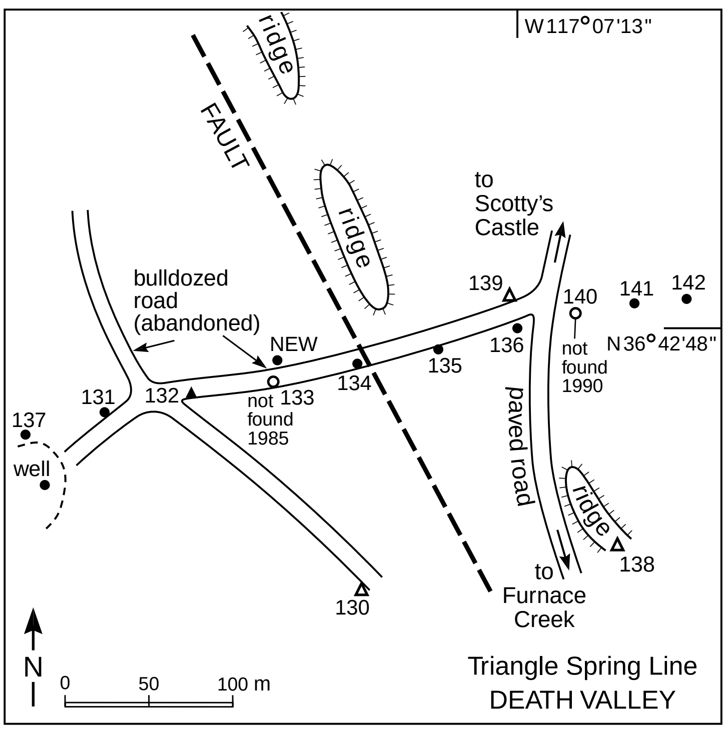
**References:**

Sylvester, A. G., and S. W. Bie, 1986. Geodetic monitoring of fault movements in Death Valley, 1970-1985, pp. 41-44, *in* Troxel, B. W., *editor*, Quaternary Tectonics of Southern Death Valley. Field Guide, Pacific Cell, Friends of the Pleistocene, 44 p.

Sylvester, A. G., 2001. Search for contemporary fault creep, Death Valley, 1970-2000, Chap. N, pp. M205-213, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

## • TRIANGLE SPRING Leveling Line Surveying Data

| SURVEY DATE | PRECISION | CLOSURE (cm) | SURVEY ORDER |
|---|---|---|---|
| 01 October 1970 | 3.301 | -0.083 | First |
| 22 December 1970 | 0.979 | 0.024 | Tectonic 1st |
| 28 August 1971 | 0.919 | 0.023 | Tectonic 1st |
| 29 March 1973 | 1.059 | 0.026 | Tectonic 1st |
| 27 March 1974 | 1.198 | 0.048 | Tectonic 1st |
| 29 April 1978 | 0.174 | 0.007 | Tectonic 1st |
| 15 January 1984 | 0.173 | -0.007 | Tectonic 1st |
| 17 December 1985 | 0.178 | 0.004 | Tectonic 1st |
| 13 December 1990 | 0.049 | -0.002 | Tectonic 1st |
| 26 March 2000 | 0.889 | 0.036 | Tectonic 1 st |




Site map of TRIANGLE SPRING leveling array across Northern Death Valley fault zone at Triangle Spring, Death Valley.

## TRIANGLE SPRING LEVELING DATA, 1970 to 2000

| BENCH MARK | DISTANCE | 1-Oct-70 | 22-Dec-70 | 8 AGU 197 | 29-Mar-73 | 27-Mar-74 | 29-Apr-78 | 15-Jan-84 | 17-Dec-85 | 26-Mar-00 |
|---|---|---|---|---|---|---|---|---|---|---|
| 142 | 0.0 | | | | | 14.09670 | 14.09660 | 14.09600 | 14.09530 | 14.09547 |
| 141 | 31.0 | | | | | 12.59770 | 12.59770 | 12.59710 | 12.59370 | 12.59666 |
| 140 | 67.5 | | | | | 10.52110 | 10.52080 | 10.52010 | 10.52040 | |
| 136 | 104.7 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 |
| 135 | 154.7 | 8.12301 | 8.12306 | 8.12292 | 8.12271 | 8.12354 | 8.12275 | 8.12195 | 8.12182 | 8.12209 |
| 134 | 204.7 | 6.15300 | 6.15292 | 6.15284 | 6.15231 | 6.15330 | 6.15242 | 6.15196 | 6.15187 | 6.15185 |
| NEW | 249.8 | | | | | 4.32663 | 4.32603 | 4.32504 | 4.32456 | 4.32316 |
| 133 | 249.8 | 4.40234 | 4.40232 | 4.40206 | | | | | | |
| 132 | 301.1 | 3.49046 | 3.49050 | 3.49012 | 3.48948 | 3.49081 | 3.49004 | 3.48909 | 3.48940 | 3.48997 |
| 131 | 355.1 | 2.09702 | 2.09707 | 2.09655 | 2.09581 | 2.09737 | 2.09653 | 2.09560 | 2.09697 | 2.09785 |
| 137 | 405.1 | 0.53931 | 0.53946 | 0.53879 | 0.53869 | 0.53998 | 0.53912 | 0.53810 | 0.53843 | 0.53849 |

# OLD GHOST Level Line (Line 100) Location Information

**Latitude:** 36°30'20"
**Longitude:** 115°52'25"

**Length:** 494 m
**Number of Bench marks:** 14

**Date of Initial Survey:** 1 October 1971
**Date of Latest Survey:** 27 March 2000

**Number of Surveys to 2001:** 7

**Trespass Permission:** Superintendent
National Park Service
Death Valley National Park
Death Valley, CA 92328

**Directions:** From Furnace Creek, proceed north about 2 miles to the entrance to the U.S. Park Service residential area. Turn right, proceed east to Old Ghost Road, turn left and proceed north and around curve to the intersection of Skyline Drive with Old Ghost Road. The center of line is about 50 m north of Old Ghost Road at this point.

**Comments:**
This line is equally disposed across the geomorphic trace of the Furnace Creek fault on the east side of Death Valley near the former site of the Park Service sewage treatment plant. This array was formerly referred to as SEWAGE before 2001. All bench marks are 1m-long copper-jacketed steel weld rods driven nearly flush to the surface of the desert floor.

**Results:**
Four levelings from January 1971 to March 2000 show no height changes among the 14 bench marks that can be attributed to vertical displacement across the fault (Sylvester and Bie, 1986; Sylvester 2001)

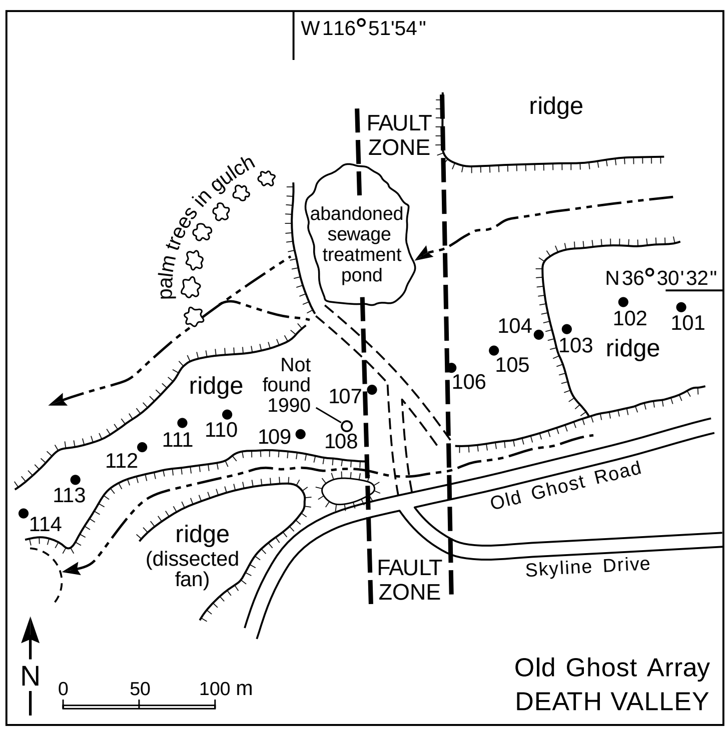
**References:**
Sylvester, A. G., and S. W. Bie, 1986. Geodetic monitoring of fault movements in Death Valley, 1970-1985, pp. 41-44, *in* Troxel, B. W., *editor*, Quaternary Tectonics of Southern Death Valley. Field Guide, Pacific Cell, Friends of the Pleistocene, 44 p.

Machette, M. N., N. C. Ninci Martinez, A. J. Crone, K. M. Haller, and G. D'Addezio, 1999. Geologic and seismic hazard investigations of the Cow Creek area, Death Valley National Park, California. U.S. Geological Survey Open-File Report 99-155, 42 p.

Sylvester, A. G., 2001. Search for contemporary fault creep, Death Valley, 1970-2000, Chap. N, pp. M205-213, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

## OLD GHOST Leveling Line Surveying Data

| SURVEY DATE | PRECISION | CLOSURE (cm) | SURVEY ORDER |
|---|---|---|---|
| 01 October 1971 | 0.820 | 0.036 | Tectonic 1st |
| 27 March 1973 | 1.096 | 0.048 | Tectonic 1st |
| 26 September 1974 | 0.921 | -0.040 | Tectonic 1st |
| 16 January 1984 | 1.266 | -0.055 | Tectonic 1st |
| 16 December 1985 | 1.325 | -0.058 | Tectonic 1st |
| 13 December 1990 | 0.232 | -0.010 | Tectonic 1st |
| 27 March 2000 | 0.304 | 0.015 | Tectonic 1 st |




Site map of OLD GHOST leveling array across northern Black Mountains fault zone near Cow Creek, Death Valley.

## OLD GHOST LEVELING DATA, 1970 to 2000

| BENCH MARK | DISTANCE | 1-Oct-71 | 27-Mar-73 | 26-Sep-74 | 16-Jan-84 | 16-Dec-85 | 13-Dec-90 | 27-Mar-00 |
|---|---|---|---|---|---|---|---|---|
| 101 | 0.0 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 |
| 102 | 40.0 | 7.75528 | 7.75537 | 7.75516 | 7.75462 | 7.75452 | 7.75453 | 7.75438 |
| 103 | 80.0 | 3.91149 | 3.91180 | 3.91130 | 3.91068 | 3.91049 | 3.91037 | 3.90957 |
| 104 | 100.0 | 1.58978 | 1.59006 | 1.58923 | 1.58810 | 1.58768 | 1.58733 | 1.58804 |
| 105 | 150.0 | -0.26731 | -0.26626 | -0.26757 | -0.26802 | -0.26833 | -0.26947 | -0.26793 |
| 106 | 180.0 | -4.68824 | -4.68713 | -4.68855 | -4.69335 | -4.69393 | -4.69462 | -4.69436 |
| 107 | 234.0 | -8.40920 | -8.40839 | -8.40921 | -8.40955 | -8.41010 | -8.41058 | -8.40951 |
| 108 | 264.0 | -10.59360 | -10.59250 | -10.59360 | -10.59330 | -10.59410 | | |
| 109 | 294.0 | -13.02590 | -13.02570 | -13.02620 | -13.02680 | -13.02670 | -13.02659 | -13.02501 |
| 110 | 344.0 | -14.48910 | -14.48900 | -14.48960 | -14.49020 | -14.48980 | -14.48944 | -14.49011 |
| 111 | 374.0 | -16.38810 | -16.38860 | -16.38870 | -16.38920 | -16.38880 | -16.38806 | -16.38940 |
| 112 | 404.0 | -18.71620 | -18.71670 | -18.71670 | -18.71780 | -18.71740 | -18.71680 | -18.71791 |
| 113 | 454.0 | -20.58990 | -20.59040 | -20.59130 | -20.59390 | -20.58380 | -20.59320 | -20.59385 |
| 114 | 494.0 | -22.83470 | -22.83520 | -22.83560 | -22.83730 | -22.83730 | -22.83731 | -22.83839 |

## VILLAGE Level Line (Line 50) Location Information

**Latitude:** 36°25’50"
**Longitude:** 116°51’07"
**Date of Initial Survey:** 21 December 1970
**Date of Latest Survey:** 27 March 2000

**Length:** 407.5m
**Number of Bench marks:** 10
**Number of Surveys to 2001:** 11

**Trespass Permission:** Notify in Advance:
Superintendent
National Park Service
Death Valley National Park
Death Valley, CA 92328
(714) 786-2331

**Directions:**
The level line is on an alluvial fan in Village Canyon east of the Badwater Road, 1.5 mile south of the Badwater turn off from Hwy 190 at Furnace Creek.

**Comments:**
Vehicles must not be driven off the paved road without the expressed and written permission of the Chief Ranger. Collect no rocks without similar permission.

The line was placed across the Artist Drive section of the Black Mountains fault zone on the east side of Death Valley one and one-half miles south of Furnace Creek Inn. It was extended an additional 47 m by adding two more bench marks at the east end of the line in 1985. This was done to have control east of bench mark 544 which, since 1970, rose 7 mm relative to the rest of the bench marks in the array. (Sylvester and Bie, 1986; Sylvester, 2001). The leveling data indicate that the height changes associated with BM 544 are aberrant relative to bench marks on either side of it, and that fault displacement has not occurred within the line (Sylvester, 2001), although a permissive case can be made that the line has tilted down to the west 11 microradians/year, mainly between 1978 and 1984 (Sylvester, 2001).

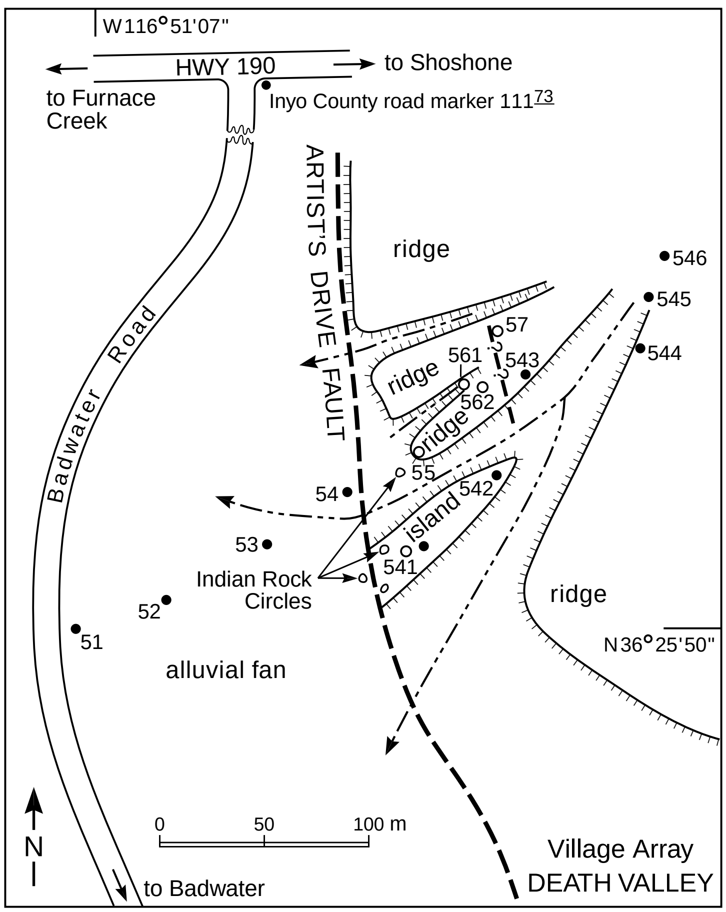
**References:**


Sylvester, A. G., and S. W. Bie, 1986. Geodetic monitoring of fault movements in Death Valley, 1970-1985, pp. 41-44, *in* Troxel, B. W., *editor*, Quaternary Tectonics of Southern Death Valley. Field Guide, Pacific Cell, Friends of the Pleistocene, 44 p.

Sylvester, A. G., 2001. Search for contemporary fault creep, Death Valley, 1970-2000, Chap. N, pp. M205-213, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

## • VILLAGE Level Line (Line 50) Data

| SURVEY DATE | PRECISION (ppm) | CLOSURE (cm) | SURVEY ORDER |
|---|---|---|---|
| 03 October 1970 | 2.434 | 0.055 | Tectonic 1 st |
| 21 December 1970 | 2.873 | 0.094 | First |
| 29 August 1971 | 7.364 | 0.042 | First |
| 21 March 1972 | 0.163 | 0.005 | Tectonic 1 st |
| 30 March 1973 | 1.792 | 0.059 | First |
| 25 September 1974 | 0.706 | -0.023 | Tectonic 1 st |
| 28 April 1978 | 2.891 | 0.095 | First |
| 15 January 1984 | 3.878 | -0.088 | First |
| 15 December 1985 | 1.236 | -0.050 | Tectonic 1 st |
| 12 December 1990 | 0.969 | 0.040 | Tectonic 1 st |
| 27 March 2001 | 0.200 | -0.008 | Tectonic 1 st |




Site map of VILLAGE leveling array across Artist Drive fault in Village Canyon, Death Valley.

## VILLAGE CANYON LEVELING DATA, 1970 to 2000

| BENCH MARK | DISTANCE | 21-Dec-70 | 21-Mar-72 | 30-Mar-73 | 25-Sep-74 | 28-Apr-78 | 15-Jan-84 | 15-Dec-85 | 12-Dec-90 | 27-Mar-00 |
|---|---|---|---|---|---|---|---|---|---|---|
| 51 | 0.0 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 |
| 52 | 46.0 | 13.77290 | 13.77300 | 13.77280 | 13.77300 | 13.77260 | 13.77310 | 13.77320 | 13.77331 | 13.77327 |
| 53 | 102.0 | 19.65220 | 19.65240 | 19.65190 | 19.65220 | 19.65100 | 19.65150 | 19.65140 | 19.65192 | 19.65205 |
| 54 | 148.0 | 23.58550 | 23.58550 | 23.58540 | 23.58540 | 23.58470 | 23.58600 | 23.58620 | 23.58673 | 23.58677 |
| 541 | 196.0 | 25.80180 | 25.80230 | 25.80200 | 25.80240 | 25.80210 | 25.80370 | 25.80390 | 25.80467 | 25.80517 |
| 542 | 246.0 | 30.44280 | 30.44320 | 30.44290 | 30.44330 | 30.44290 | 30.44490 | 30.44510 | 30.44569 | 30.44601 |
| 543 | 296.0 | 35.01910 | 35.01930 | 35.01890 | 35.01930 | 35.01900 | 35.02130 | 35.02170 | 35.02220 | 35.02291 |
| 544 | 353.0 | 39.40240 | 39.40310 | 39.40270 | 39.40380 | 39.40490 | 39.40820 | 39.40900 | 39.41016 | 39.41198 |
| 545 | 377.0 | | | | | | | 41.65340 | 41.65424 | 41.65526 |
| 546 | 400.0 | | | | | | | 44.15870 | 44.15929 | 44.16004 |

## HANAUPAH CANYON Level Line (Line 70) Location Information

**Latitude:** 36°14'05"
**Longitude:** 116°53'00"

**Length:** 321 m
**Number of Bench marks:** 10

**Date of Initial Survey:** 2 October 1970
**Date of Latest Survey:** 26 March 2000

**Number of Surveys to 2001:** 9

**Trespass Permission:** Superintendent
National Park Service
Death Valley National Park
Death Valley, CA 92328
(714) 786-2331

**Directions:**
From Furnace Creek, proceed south toward Badwater, thence southwest on the Westside Road about 5 miles to Shorty's Well. Turn right and continue about 0.5 mile on a dirt road that proceeds west up the Hanaupah fan.

**Comments:**
This short line crosses the Hanaupah fault west of Shorty's well on the west side of Death Valley. The east half of the line is 15 m south of the dirt road that leads up the fan. The line crosses the road at the first, sharp left bend, and it proceeds across the fault in a little canyon incised into the fault scarp. Bench mark 69 was added in 1974.

**Results:**
Height changes among the eight bench marks are less than 1mm between 1974 and 2000.

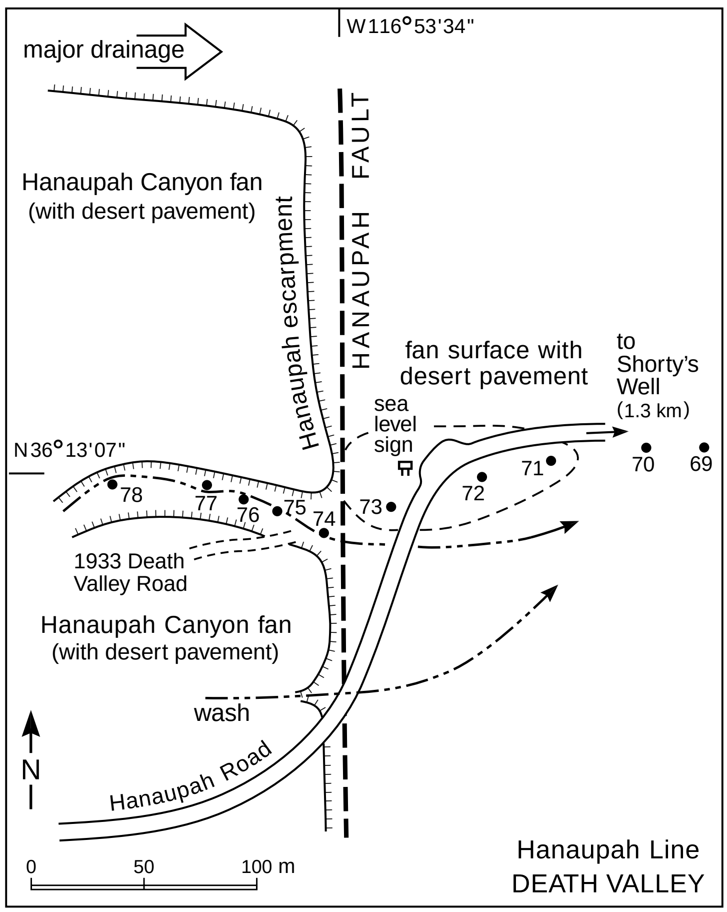
**References:**

Sylvester, A. G., and S. W. Bie, 1986. Geodetic monitoring of fault movements in Death Valley, 1970-1985, pp. 41-44, *in* Troxel, B. W., *editor*, Quaternary Tectonics of Southern Death Valley. Field Guide, Pacific Cell, Friends of the Pleistocene, 44 p.

Sylvester, A. G., 2001. Search for contemporary fault creep, Death Valley, 1970-2000, Chap. N, pp. M205-213, *in* Machette, M. N., M. L. Johnson, and J. L. Slate, *editors*, Quaternary and Late Pliocene Geology of the Death Valley Region: Recent Observations on Tectonics, Stratigraphy, and Lake Cycles (Guidebook for the 2001 Pacific Cell – Friends of the Pleistocene Fieldtrip). U.S. Geological Survey Open-File Report 01-51, 246 p.

## • HANAUPAH CANYON Level Line Surveying Data

| SURVEY DATE | PRECISION | CLOSURE (cm) | SURVEY ORDER |
|---|---|---|---|
| 02 October 1970 | 0.599 | -0.014 | Tectonic 1st |
| 02 October 1971 | 1.006 | 0.024 | Tectonic 1st |
| 20 March 1972 | 1.648 | 0.038 | Tectonic 1st |
| 28 March 1973 | 1.970 | 0.046 | Tectonic 1st |
| 28 March 1974 | 1.349 | 0.041 | Tectonic 1st |
| 29 April 1978 | 2.374 | -0.055 | First |
| 15 January 1984 | 0.451 | 0.011 | Tectonic 1st |
| 15 December 1985 | 0.256 | -0.006 | Tectonic 1st |
| 11 December 1990 | 1.502 | -0.046 | Tectonic 1st |
| 26 March 2000 | 0.530 | -0.017 | Tectonic 1 st |




Site map of HANAUPAH leveling arrays across Hanaupah fault
near base of Hanuapah Canyon fan, Death Valley.

## HANAUPAH LEVELING DATA 1970 to 2000

| BENCH MARK | DISTANCE | 2-Oct-70 | 2-Oct-71 | 20-Mar-72 | 28-Mar-73 | 28-Mar-74 | 29-Apr-78 | 15-Jan-84 | 15-Dec-85 | 11-Dec-90 | 26-Mar-00 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 69 | -60.0 | | | | | 5.32261 | | | | 5.32215 | 5.32175 |
| 70 | -30.0 | | | | | 6.71102 | | | | 6.71111 | 6.71228 |
| 71 | 0.0 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 | 10.00000 |
| 72 | 32.0 | 12.34860 | 12.34860 | 12.34840 | 12.34850 | 12.34860 | 12.34860 | 12.34850 | 12.34840 | 12.34770 | 12.34768 |
| 73 | 73.5 | 15.48080 | 15.48090 | 15.48070 | 15.48070 | 15.48070 | 15.48070 | 15.48070 | 15.48070 | 15.47990 | 15.47981 |
| 74 | 106.5 | 17.83750 | 17.83720 | 17.83700 | 17.83760 | 17.83730 | 17.83740 | 17.83680 | 17.83650 | 17.83570 | 17.83505 |
| 75 | 136.5 | 19.71560 | 19.71540 | 19.71530 | 19.71590 | 19.71570 | 19.71580 | 19.71570 | 19.71540 | 19.71440 | 19.71442 |
| 76 | 156.0 | 21.95520 | 21.95500 | 21.95480 | 21.95540 | 21.95530 | 21.95540 | 21.95510 | 21.95510 | 21.95400 | 21.95400 |
| 77 | 178.5 | 23.77260 | 23.77240 | 23.77210 | 23.77270 | 23.77260 | 23.77260 | 23.77250 | 23.77230 | 23.77120 | 23.77140 |
| 78 | 231.0 | 27.50550 | 27.50520 | 27.50480 | 27.50550 | 27.50510 | 27.50550 | 27.50520 | 27.50540 | 27.50410 | 27.50424 |