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GEOLOGICAL SURVEY

PRECISION GRAVITY NETWORK FOR MONITORING THE LASSEN GEOTHERMAL SYSTEM, NORTHERN CALIFORNIA

by

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Abstract

A precision gravity network consisting of approximately 50 stations was established to monitor the Lassen geothermal system. The network was surveyed during the summer of 1982 and tied to a similar network established in 1981. Measurements yielded relative gravity values at the network stations with average uncertainties of 0.007 mGal (1 computed standard error).

Introduction

Lassen Volcanic National Park in northern California contains numerous spectacular hydrothermal features including fumaroles and hot springs at Sulphur Works, Bumpass Hell, Little Hot Springs Valley, Boiling Springs Lake, and Devil's Kitchen (plate 1). These features give the Park a distinctive character and constitute major tourist attractions. Similar, though less spectacular, hydrothermal features are present in the Lassen Known Geothermal Resources Area (KGRA) located adjacent to and south of Lassen Volcanic National Park. Data from geologic and geochemical investigations suggest that hydrologic connection may exist between the hydrothermal systems beneath Lassen Volcanic National Park and Lassen KGRA (Müffler and others, 1982). If the systems are connected, then development of the geothermal resources in the Lassen KGRA and production of geothermal fluids could affect the hydrothermal features in the National Park, perhaps adversely. With this possibility in mind, during the summer of 1982 we began a program of repeat precision gravity measurements within the KGRA and the National Park in order to provide the base-line data for monitoring possible future changes in the mass of water in the subsurface.

Repetitive gravity surveys have been used successfully to monitor geothermal systems in other areas. Hunt (1970, 1977), in his pioneering work in the Wairakei, New Zealand, geothermal field, found gravity decreases as

large as 0.5 mGal associated with the extraction of water (both liquid and gas phases) for the generation of electricity. These gravity data combined with data on the volume of fluid extracted allowed him to delineate the areas from which the water was being depleted and to estimate the amount of fluid recharge during the period of production. In a similar study at The Geysers, California, Isherwood (1977) used repeat gravity data to define the region from which fluid was extracted. He concluded that, within the accuracy of the data, the fluids extracted from this field were not replaced by recharge.

For monitoring the Lassen geothermal system, a network of approximately 50 stations (plate 1) was established and measured using techniques and procedures developed for studying crustal deformation and the movement of subsurface fluids associated with tectonic and volcanic activity (Jachens, 1979; Jachens and Eaton, 1980). This network includes a few stations that had been measured in 1981 as part of a volcano monitor program (Jachens and others, 1983) and includes remote stations at Manzanita Lake and in the Sierra Nevada south of Lake Almanor.

Gravity Measurement Procedures and Reductions

Detailed descriptions of the gravity stations are contained in Appendix A and in Jachens and others (1983). Unless otherwise noted, each gravity station is marked with a 3.5 cm diameter brass disc stamped with the station designator. In addition, three shallow leg-holes were drilled into the rock at each site to mark the precise location of the gravimeter reading dish. The gravimeters were read with the operator facing north at all stations described in Appendix A. All reading sites are marked and described such that the reading position of the gravimeters can be recovered to better than 1 cm vertically and 3 cm horizontally, and the reading orientation can be recovered to within approximately 10°.

Relative gravity with respect to station LPG10 was measured at each station using LaCoste and Romberg model G and D gravimeters equipped with electronic readout. The measurements were taken along closed circuits with reference station measurements typically repeated every 4-5 hours. Each station was measured during at least two circuits with a set of 3 gravimeters.

The gravimeter readings were converted to gravity units using the calibration tables provided by the manufacturer, modified according to the results of measurements taken over the U.S. Geological Survey's Mt. Hamilton calibration range (Barnes and others, 1969). The correction factors applied to the calibration tables of the gravimeters used in this study are given in table 1.

Earth tide corrections were applied to all measurements according to the formulation of Longman (1959), with an assumed compliance factor of 1.160. The data were then analyzed by means of a least squares procedure with system unknowns that include the relative gravity between field stations and the local reference station and the coefficients of time dependent drift polynomials. Based on a study of the drift characteristics of LaCoste and Romberg gravimeters (Jachens, 1979), each day's run with each gravimeter was assumed to be represented by an independent drift polynomial. A first order polynomial was assumed if the reference station was measured only twice during a day and a second order polynomial was assumed for the data from days with three reference station measurements. The drift terms in the analyses include both actual gravimeter drift and inaccuracies in the applied tidal correction such as might arise from the influence of ocean tides.

Table 1 -- Gravimeter correction factors

Gravimeter	Correction Factor
D26	1.0010
G8	1.00061
G161	1.00057

Gravity values at all stations relative to LPG10 are given in Table 2. Uncertainties associated with the relative gravity values average approximately 0.007 mGal (1 computed standard error)

Changes between the relative gravity values obtained in this survey and those obtained in any subsequent surveys will have uncertainties defined by $s.e._{1,2} = [(s.e._1)^2+(s.e._2)^2]^{1/2}$ where $s.e._{1,2}$ is the computed standard error of the gravity difference and $s.e._1$ and $s.e._2$ are the computed standard errors of the relative gravity values from the two surveys. If uncertainties similar to those in the present survey are obtained in subseqent surveys, then standard errors of about 0.010 mGal can be expected for the measured gravity changes at the stations of this network. Removal or addition of a layer of water 25 cm thick would cause a gravity change of approximately 0.010 mGal.

STATION	RELATIVE GRAVITY	STANDARD ERROR	STATION	RELATIVE GRAVITY	STANDARD ERROR
LP001	-34.055	0.0054	LPG38	-150.582	0.0062
LP001A	-34.204	0.0054	LPG39	-174.128	0.0062
LP049A	-207.516	0.0063	LPG40	-163.952	0.0063
LP144	-125.420	0.0078	LPG41	-161.236	0.0063
LP144A	-123.502	0.0086	LPG42	11.367	0.0069
LPG10A	-0.066	0.0030	LPG42A	11.431	0.0068
LPG11	-51.356	0.0080	LPG43	54.558	0.0067
LPG12	-49.306	0.0080	LPG43B	54.695	0.0068
LPG13	-58.763	0.0079	LPG44	-33.483	0.0064
LPG14	-66.864	0.0079	LPG45	-43.874	0.0065
LPG15	-71.000	0.0079	LPG46	-55.230	0.0065
LPG16	-67.880	0.0071	LPG50	-217.449	0.0064
LPG17	-71.989	0.0070	LPG50A	-216.717	0.0064
LPG18	-65.706	0.0071	LPG51	-250.359	0.0077
LPG19	-66.253	0.0072	LPG51A	-250.455	0.0077
LPG20	-48.872	0.0071	LPG52	-152.461	0.0064
LPG21	-37.375	0.0071	LPG52A	-152.530	0.0070
LPG22	-27.952	0.0071	LPG53	-165.597	0.0063
LPG23	-26.288	0.0071	LPG53A	-165.628	0.0063
LPG24	-25.849	0.0078	LPG54	-147.867	0.0091
LPG25	-91.963	0.0071	LPG54A	-147.548	0.0091
LPG26	-98.698	0.0071	LPG55	-134.929	0.0062
LPG27	-83.647	0.0066	LPG55A	-135.613	0.0062
LPG28	-81.733	0.0064	LPG56	-83.765	0.0063
LPG29	-78.920	0.0063	LPG56A	-83.543	0.0063
LPG30	-47.739	0.0062	ML7	-46.187	0.0056
LPG31	-23.167	0.0072	ML7A	-46.195	0.0056
LPG32	7.213	0.0078	ML8	-110.707	0.0055
LPG33	-65.997	0.0063	ML8A	-110.597	0.0055
LPG34	-85.151	0.0062	SALTUS	-218.952	0.0069
LPG35	-93.476	0.0061	WILSON	-36.297	0.0080
LPG36	-103.121	0.0068	BERT	-202.975	0.0070

Table 2 -- Gravity (in mGal) at network stations relative to LPG10. The observed gravity value at LPG10 is 979,775.31 mGal based on a value at ML8 (979,664.60 mGal) given by Robbins and others (1976).

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Appendiz A -- Descriptions of precision gravity stations. These descriptions should be used with the map locations shown on Plate 1 and with the road mileage diagram in Plate 1 (inset). Road station positions given on plate 1 are only approximate.

LPG10

Primary base station located 1.43 mi southeast along Highways 36 and 89 from the office and restaurant at Childs Meadows Lodge, 0.39 mi northwest along Highways 36 and 89 from intersection with Willow Lake Road, 25 m northeast of and 2.5 m above centerline of Highways 36 and 89, on a 1.5 x 2 m boulder projecting 1 m above ground.

LPG10A

21 m 335° from LPG10, on a 1.5 m diameter boulder projecting 1 m above ground.

LPG11

15 m south of and 6 m above centerline of road, on top of a large outcrop. Outcrop is about 2 x 2 m on top and has a 2 m high face facing north.

LPG12

20.0 m south of and 3 m above centerline of road, on a 2 x 2.5 m boulder (outcrop?) projecting 1 m above ground.

LPG13

15 m west of centerline of road, on a 2 x 2 m boulder projecting 0.5 m above ground.

LPG14

21.5 m 145° from center of intersection of main road and side road leading due east, on a low, rounded 0.5 m diameter boulder projecting 0.2 m above ground.

LPG15

16.0 m west of centerline of road, on a 2 x 2.5 m boulder projecting 1 m above ground.

LPG16

41 m east along road from culvert where road crosses South Arm Rice Creek, then 13.9 m south of centerline of road, on 1 m diameter boulder projecting 0.7 m above ground.

LPG17

12.0 m east of and 4 m above centerline of road, on 1 x 1.5 m boulder projecting 1.5 m above ground.

LPG18

23.3 m southeast of centerline of road, 1.5 m south of a 1 m diameter, 0.5 m high stump, on a low, rounded 0.5 x 1 m boulder projecting 0.1 m above ground.

LPG19

12.7 m north of centerline of road, 1 m west of a 0.5 m diameter Jeffrey pine, on a low, rounded 0.5 x 1 m boulder.

LPG20

13.3 m south of centerline of road, near edge of creek, on a flat, low 1 x 1 m boulder flush with ground.

LPG21

8.8 m northeast of centerline of road, on a flat, low 1 x 1 m boulder projecting 0.2 m above ground.

LPG22

14.2 m south of centerline of road, on a 1 x 1 m boulder at edge of creek.

LPG23

14.2 m south of centerline of road, near center of top of large, rounded 10 m long outcrop.

LPG24

15 m north of and 4 m above centerline of road, on top and in center of a 1.5 x 2.5 m boulder projecting 2 m above ground.

LPG25

At "turnaround" at north end of road that parallels South Arm Rice Creek. 25 m south of north edge of, 15.4 m west of centerline of, 2.5 m above "turnaround", and 8.4 m 310° from a 1 m diameter stump at west edge of "turnaround", on 1 x 1.5 m boulder projecting 0.5 m above ground.

LPG26

50 m 340° from north end and 2 m above "turnaround" at north end of road leading toward Ridge Lake, on top of 10 x 20 m outcrop projecting 1.5 m above ground.

LPG27

20 m southwest of centerline of road, 15.6 m 235° from southwest end of metal culvert under road, on a 1 x 2 m boulder projecting 1 m above ground.

LPG28

16.0 m south of centerline of road, on a low, rounded 0.5 x 1 m boulder projecting 0.3 m above ground.

LPG29

13.6 m 50° from and 1 m above center of T junction at north end of west road to Little Willow Lake, on low, rounded boulder almost flush with ground.

LPG30

11.7 m southwest of centerline of road, on 1.5 m diameter boulder projecting 1.5 m above ground.

LPG31

15 m northwest of and 2.5 m above centerline of road, northwest of and 6.5 m above north end of Wilson Lake, on 2.5 m diameter boulder.

LPG32

Roughly 20 m northwest of centerline of Highways 36 and 89, on 1 x 2.5 m boulder projecting 1.5 m above ground.

LPG33

17.1 m east of and 2.5 m above centerline of Highway 89, at top of cutbank, on top of 0.5 x 1 m boulder projecting 0.5 m above ground.

LPG34

9.1 m west of and 2 m above centerline of Highway 89, at top of road cut on a 2.5 m diameter boulder projecting 0.5 m above ground.

LPG35

9.5 m west of centerline of Highway 89 and a few meters east of a 1.8 x 2.5 m rock projecting 1.5 m above ground, on a low 0.5 m diameter rock.

LPG36

4.3 m west of and 1 m above centerline of Highway 89 at Lassen Volcanic National Park boundary, on top of stone and concrete wall.

LPG38

Southeast of Highway 89, at sharp turn southeast of Diamond Peak, approximately 6 m below road and down slope from the parking area, on a triangular 2.5 x 2.5 x 2.5 m outcrop.

LPG39

12 m west of centerline of Highway 89, at large pull-out north of Diamond Peak switchbacks, at highest point of road-cut, on a 0.5 x 0.5 m boulder projecting 0.2 m above ground.

LPG40

200 m along road to Kings Creek Picnic area from junction with Highway 89, 15 m north of centerline of road, on a 1 x 2 m rock projecting 0.8 m above ground.

LPG41

30 m east of centerline of Highway 89, at first large pull-out north of mile 33, on a 1 x 1.5 m boulder projecting 0.5 m above ground.

LPG42

From Highway 89 east of Canyon Dam, follow Seneca Road 0.3 mi. Station is at top of a drop-off, 40 m north of a turnout and 6 m above road, on a large flat rock.

LPG42A

5.5 m north of LPG42, below a large round rock.

LPG43

From Highway 89 east of Canyon Dam, follow Seneca Road 5.6 mi to a bridge. Station is west of road 12 m east of bridge, on a flat rock.

LPG43B

Opposite LPG43, 4 m northeast of centerline of road, on a low flat rock.

LPG44

12 m south of south edge of cattle guard at the Warner Valley entrance to Lassen Volcanic National Park, on a 0.5 m diameter boulder projecting 0.3 m above ground.

LPG45

1.8 m southeast of the chimney on the east side of the Warner Valley Ranger Station, on a 1 x 3 m outcrop projecting 0.1 m above ground.

LPG46

6 m north of the centerline of road, on a 1 x 1 m boulder projecting 0.5 m above ground.

LPG50

On Mount Conard, on ridge line approximately 300 m north of summit, 5 m north of a 1 m high White pine and 6 m west of a 2 m high juniper, on a 0.5 x 0.5 m rock.

LPG50A

10 m north of and 3 m lower than LPG50, on rock at ridge line.

LPG51

In southern part of small meadow just north of summit of Bumpass Mountain, 10 m east of a 2.5 m high cliff, on a 1.5 x 2 m rock projecting 0.5 m above ground.

LPG51A

51A

6 m 220° from LPG51, on a 2 x 2 m rock projecting 1 m above ground.

LPG52

30 m east-southeast of east end of unnamed lake, on low ridge between lake and cliff above Devil's Kitchen, on rock outcrop.

LPG52A

On rock 3.5 m east of LGP52

LPG53

60 m 160° from small unnamed lake, 8 m above lake, near crest of ridge, on a 1 m diameter rock projecting 0.5 m above ground.

LPG53A

10 m 0° from LPG53, on a 0.3 x 1 m rock projecting 0.3 m above ground.

LPG54

80 m north of south edge and at east edge of clearing near summit of first mountain west of Drake Lake and south of Devils Kitchen, adjacent to and at top of 4 m cliff facing east, on a 1 x 2 m flat rock projecting 0.5 m above ground.

LPG54A

roughly 20 m south of LPG54, on rock at base of large outcrop.

LPG55

At south boundary of Lassen Volcanic National Park, over NPS benchmark "A103 1977", near southwest edge of top of knob, 6 m northwest of a large dead tree, on a flat rock.

LPG55A

10 m east of LGP55, on a 1 m diameter boulder projecting 0.5 m above ground.

LPG56

In clearing 0.5 km northwest of Terminal Geyser, approximately 60 m northwest of line of trees that cross the clearing near its center, 6 m northeast of southwest edge of clearing, on a 2.5 x 2.5 m rock projecting 0.5 m above ground.

LPG56A

3.5 m southeast of LPG56, on a low 0.5 x 1 m rock.

BERT

15 m west of and 5 m above centerline of Highway 89, between southernmost shore of Emerald Lake and the road, on a 1 m diameter rock projecting 0.3 m above ground.

SALTUS

Approximately 250 m east of Lake Helen, 25 m north of centerline of Highway 89, on a 2 x 3 m rock projecting 1 m above ground.

WILSON

100 m 255° from intersection of Wilson Lake Road and road along Wild Cattle Mountain, approximately 10 m above road, on 1 x 1 m boulder projecting 0.5 m above surface and containing benchmark stamped "WILSON 1". Center of gravimeter base plate 0.5 m 320° from benchmark.