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Field Trip to Oklahoma's LIP (Large Igneous Province)

A Tribute to R.E. (Tim) Denison

Neil H. Suneson, OGS Geologist IV

On March 8, 2014, 37 geologists, geophysicists, and students from as far north as Ottawa, Ontario, and as far east as Pittsburgh, Pennsylvania, gathered in Sulphur, Oklahoma, to review and expand upon the ongoing work on the igneous rocks of the Southern Oklahoma Aulacogen (SOA) (Figure 1). This meeting was designed to be more formal than an earlier one held several years ago; a wide net was cast for participants, and a guidebook (albeit preliminary) was prepared.

Day one included three stops under cold, dreary skies, the threat of rain, and a (seemingly) 140 mph north wind. The diabase dike swarm at the Mill Creek Quarry (Stop 1) impressed even those who had seen it before, and Tim Denison reminded us how difficult it was to map the easily weathered mafic rocks before the quarry was established. Stop 2 started at the top of Signal Mountain. Richard Hanson described the geology of the mountain – two rhyolite flows separated by a unit of rhyolitic volcaniclastic rocks and intruded by diabase dikes and irregularly shaped hypabyssal rhyolite intrusions. The upper rhyolite flow is at least 2000 ft thick; this begins to hint not only at the enormous volume of the igneous rocks in the SOA but at the impressive size of some individual lava flows. The participants split into two groups. About 25 descended off the northeast side of Signal Mountain with Hanson to look at the volcanic stratigraphy and some of the features in the rhyolites. The remainder followed Bob Puckett into Turner Falls Park to look at the volcanic and intrusive rocks mapped there by Amy Eschberger as part of her MS thesis at TCU.

Stop 3 was to have been the basalt vent complex at the Hanson Aggregates Quarry, but despite repeated requests, we were not allowed entry.

That evening Hanson and Puckett displayed some of the rocks we would have seen at the Hanson Quarry and the igneous cuttings from a number of wells in the area (Figure 2). Key to the discussions that ensued over the rocks, beer, and wine was the complexity of some of the volcanic lithologies and textures that are preserved in these Cambrian rocks and the usefulness of the cuttings in unraveling geology that isn't exposed on the surface. Detailed mapping of the volcanic rocks and petrographic and geochemical studies of surface and subsurface samples has truly

Figure 1

led to a greater understanding of this part of Oklahoma's geological history.

The highlight of the evening was State Geologist Randy Keller's announcement that the guidebook for the field trip was being published as a tribute to Tim Denison (serendipitously) on the 50th anniversary of his seminal study of the basement rocks of Oklahoma (Ham et al., 1964). Keller's tribute to one of the stalwarts of Oklahoma geology was applauded by the participants, all of whom considered themselves privileged to have Tim as a participant on the field trip.

Unlike the day before, Sunday (March 9) started off beautifully. Jon Price and Richard Hanson led the field trip for most of the day, starting with an overview of the Wichita Mountains from the top of Mount Scott in the Wichita Mountains National Wildlife Refuge. For those who had never been there, it hardly seemed like Oklahoma, but it did seem like the perfect place for a group photograph (Figure 1). The group made a circuit of the parking area, and Price pointed out the evidence for a Permian paleogeography, the rounded Carlton Rhyolite hills of Ft. Sill, and the prominent treeline (gabbro – granite contact) on Mount Sheridan. The second stop of the day was a roadcut along Hwy. 58 north of Lake Lawtonka of the Carlton Rhyolite and a diabase dike (Figure 3). Hanson and his students have mapped seven rhyolite flows in the Blue Creek Canyon area of the Slick Hills.

After lunch, Price took the group to an outcrop of Mount Scott Granite that had been intruded by diabase dikes and described a

Rodger E. "Tim" Denison – A Tribute

G. Randy Keller, Oklahoma State Geologist

Tim obtained his B.S. (1954) and M.S. (1959) degrees from the University of Oklahoma (OU), and he began his love affair with basement rocks at OU and the Oklahoma Geological Survey (OGS). Tim worked for the OGS in the late 50s and early 60s, mainly with W.E. "Bill" Ham on the Survey's classic Bulletin 95 – "*Basement Rocks and Structural Evolution of Southern Oklahoma.*" Several of his OGS publications on basement rocks are still benchmarks used in all subsequent studies.

In the early 1960s, William R. Muehlberger began his American Association of Petroleum Geologists-supported project on the basement rocks of North America. In what Bill describes as "a great stroke of luck," he discovered Tim was working on a similar project for the OGS. Bill found that Tim was interested in expanding his study to include basement rocks from across middle North America as a Ph.D. aspirant at the University of Texas – Austin (UT). Tim, along with fellow student Edward Lidiak, pieced together the hidden roots of central North America, primarily by studying samples of basement rock recovered in dozens of deep petroleum exploration wells. Tim's fundamental work put the isolated basement-rock outcrops in Oklahoma, Texas, Kansas, Missouri, and Arkansas, along with the more extensive exposures in New Mexico, Colorado, and Wyoming, into a regional perspective. In 1966, Tim received his Ph.D. from UT.

After a productive career at the Mobil Research and Development Lab, where he worked on projects concerning sedimentary geochemistry, Tim became a research scientist at the University of Texas at Dallas. Tim became well known as one of the pioneers in the field of "strontium stratigraphy." He was a leader in efforts that showed strontium isotopic systematics of carbonate and evaporite deposits record the chemical evolution of seawater during the Phanerozoic. In this field, Tim is the second author of a Geology paper with almost 900 citations!

Finally, Tim continues to generously share his insights with many colleagues and students and has also been a strong supporter of the geology programs at both OU and UT for many years.

Cover photo: Figure 1. Participants in the OGS-sponsored field conference on the igneous rocks and tectonic history of the SOA at the top of Mount Scott. From left to right, front row: Dena Hanson (Ft. Worth), Richard Hanson (TCU), Kari Bickhard (MWSU), Darlene Simpson (MWSU), Molly Lord (MWSU), Neil Suneson (OGS), Jonathan Price (MWSU), Jock Campbell (OGS). Second row, standing: Tim Denison (Dallas), Ed Lidiak (University of Pittsburg), Asish Basu (UT Dallas), Brian Cardott (OGS), Brennan Jordan (University of South Dakota), Tom Olsen (Quintin-Little Co.), Matt Brueseke (KSU), Bill Thomas (Geological Survey of Alabama), Melanie Barnes (Texas Tech University), Anna Downey (KSU), Peter Anderson (University of Houston), Matt Ledvina (UT Austin), Bob Stern (UT Dallas), Peter Michael (University of Tulsa), Randy Keller (OGS and OU), Wouter Bleeker (Geological Survey of Canada), Amberlee Darold (OGS), Charles Gilbert (OU), Molly Carpenter (Chesapeake Energy), Brent Elliot (UT Austin), Bob Puckett (Oklahoma City). Third row, sitting or standing on Mount Scott Granite: Jasper Hobbs (KSU), Joseph Boro (TCU), Jeanne Fromm (University of South Dakota), Rich Kyle (UT Austin), Courtney Bartlett (MWSU), Chelsea Toews (TCU), Stan Paxton (USGS Oklahoma City), Katrin Puckett (Oklahoma City). Abbreviations: KSU – Kansas State University; MWSW – Midwestern State University; OGS – Oklahoma Geological Survey; OU – University of Oklahoma; TCU – Texas Christian University; UT – University of Texas. Photograph by Kevin Crain (OGS).

Figure 2. Richard Hanson (TCU) and samples of volcanic rocks from the Hanson Aggregates Quarry and other localities in the SOA. Photograph by Bob Puckett.

variety of features that were evidence that the granite must have been "warm" when the dikes intruded. This, in turn, suggested to Price that the dikes formed shortly after the granite had been emplaced and was further evidence for the coincidence of mafic and silicic magmatism. The Cambrian – Permian unconformity is well exposed at Quetone Overlook within the refuge and just west of the road to the top of Mount Scott. Here, Price described the geomorphic evidence that the headless canyons in the granite represent Permian erosional features. Hanson and Price also discussed the geology of the immediate area based on their detailed mapping, and agreed that the stratigraphic sequence is, from bottom to top, Davidson Metarhyolite\Carlton Rhyolite\Mount Scott Granite\Post Oak Conglomerate. The last formal stop of the day was farther west along Hwy. 49 in the refuge at the new Burford Lake Geology Interpretive Trail. The group walked the short trail and viewed the new signs being installed describing the geology of the SOA and the two main rock types that can be seen — gabbro and granite (Figure 4). The establishment of a geology nature trail—the first of its kind in Oklahoma—is a cooperative endeavor by the Red Earth Desk and Derrick Club of Oklahoma City, the OGS, the OU ConocoPhillips School of Geology and Geophysics, and the Wichita Mountains National Wildlife Refuge.

At the end of the trip, the participants said their goodbyes and split up to head home – some south back to Austin, others north to Manhattan, others for even more distant places. Hanson offered to add an informal third day for those who wanted to stay to look at some of the plutonic mafic rocks near the refuge and to further examine the rhyolite section in the Slick Hills, and several accepted. Many promised further and continued collaboration on working on this part of Oklahoma's "basement", and all agreed it was a great two days.

Special Thanks

The field-trip leaders would like to thank a number of organizations and individuals for making this field trip a success. Martin-Marietta has always been a wonderful host for the many geological field groups that have wanted to see the dike swarm at their Mill Creek Quarry, and they were for us. A special thank you goes to Jason Parker for showing us around on that cold, dreary Saturday morning. Fred Chapman and Ruth Coffey (both of the Chapman Ranch) have very graciously allowed us access to their ranch land, not only for this field trip but for continued work on the volcanic rocks in the East Timbered Hills. The City of Davis granted Hanson and his students access to their land, cheap "lodging" at their campground, and free admission to all

Figure 3. Line of vans and congregation of geologists at Carlton Rhyolite outcrop (Stop 4) in Slick Hills, north of Lake Lawtonka.

In This Issue. . .

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field-trip participants to Turner Falls Park on the day of our trip. The Super 8 Motel in Lawton turned their dining area over to us for our Saturday night rock fest. I (NS) could not have organized the field trip without Michelle Summers' help; few (and especially me) can remember all the details that go into running a field trip, but Michelle can. Here's hoping I retire before she does.

References

Ham, W.E., Denison, R.E., and Merritt, C.A., 1964, Basement rocks and structural evolution of southern Oklahoma: Oklahoma Geological Survey Bulletin 95, 302p.

Taff, J.A., 1904, Preliminary report on the geology of the Arbuckle and Wichita Mountains in Indian Territory and Oklahoma: U.S. Geological Survey Professional Paper 31, 93p.

Figure 4. One of six signs along the Burford Lake trail describing the geology of the SOA. This sign is about Oklahoma's "gold rush" of 1901 to 1907. The U.S. Geological Survey sampled the mines and concluded they showed a "uniform absence of even a trace of gold" (Taff, 1904, p. 92).

Workshops, Meetings, Conferences, and Field Trips – *2014*

September 5 — **2014 Real Deal Mid-Continent Prospect Expo**
Oklahoma City, Oklahoma; sponsored by Oklahoma City Geological Society and Oklahoma Geological Survey; contact: Chelsey Jones at 405/236-8086, x17; e-mail: cjones@ocgs.org

Sept. 13-16 — **American Institute of Professional Geologists (AIPG) & AHS Annual Meeting**
Prescott, Arizona; contact: 303/412-6205; website: http://www.aipg.org

Sept. 24-25 — **13th Annual Osage Minerals Council Oil & Gas Summit & Lease Sale**
Tulsa, Oklahoma; contact: Rick Torix at 202/527-5137, e-mail: ricky@Lanetorix.com, or Fawn Cheshewalla at 918/287-5346, e-mail: fcheshewalla@osagenation-nsn.gov; website: www.osagetribe.com

Sept. 27-Oct. 3 — **The Society for Organic Petrology 2014 (TSOP)**
Sydney, Australia; website: http://www.tsop.org

Sept. 28 — **Science in Action**
Norman, Oklahoma; sponsored by Sam Noble Museum of Natural History - free museum admission; contact: Brittany Pritchett, Oklahoma Geological Survey, 405/325-7331 or 800/330-3996; e-mail: brittanyp@ou.edu; website: www.snomnh.ou.edu

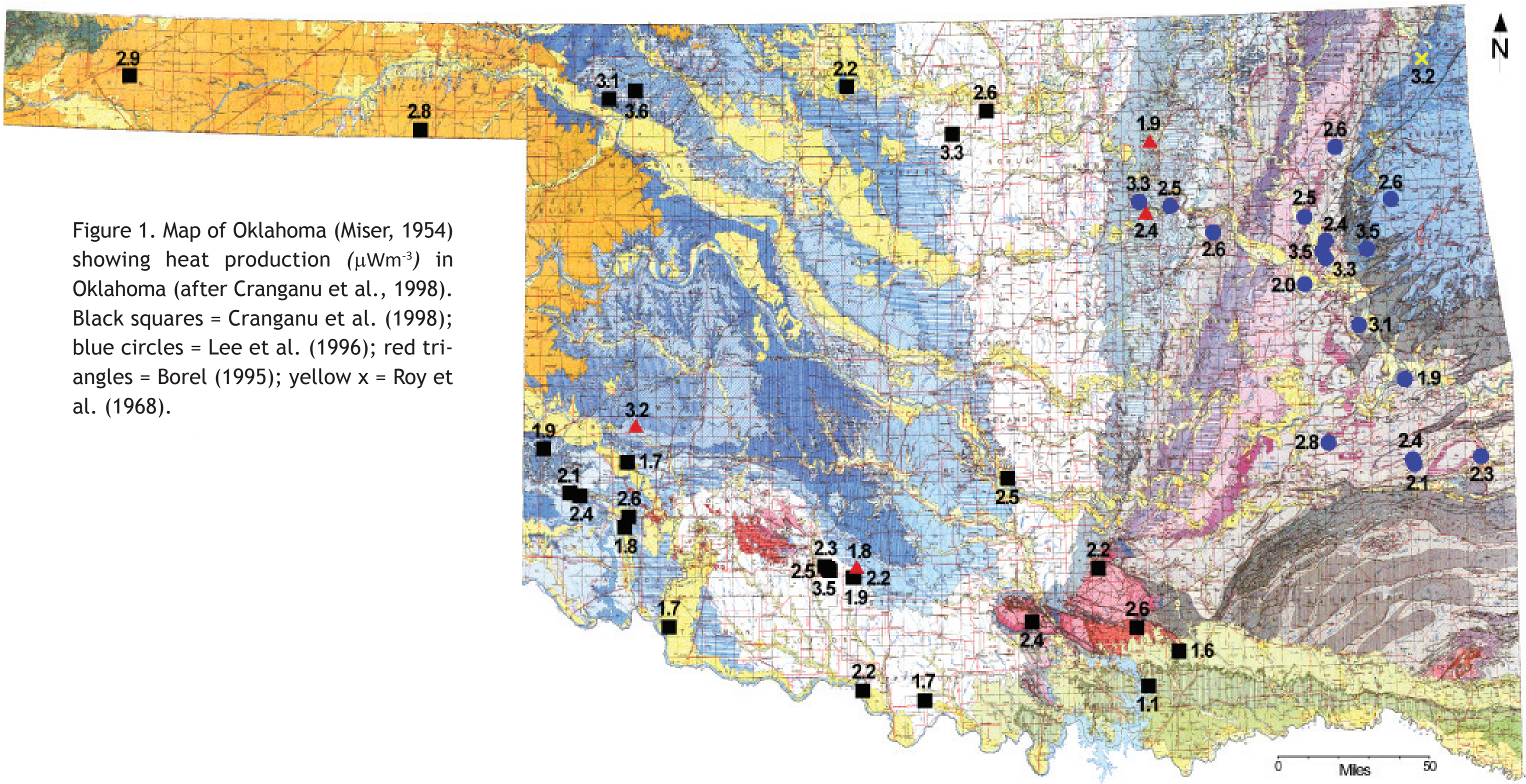

Figure 1. Map of Oklahoma (Miser, 1954) showing heat production (μWm^{-3}) in Oklahoma (after Cranganu et al., 1998). Black squares = Cranganu et al. (1998); blue circles = Lee et al. (1996); red triangles = Borel (1995); yellow x = Roy et al. (1968).

Summary of New Heat Production Calculations in Oklahoma

Julie M. Chang, OGS Geologist IV

Introduction

This article is an update to the article "Heat production in Oklahoma: Old and new data," published in the *Oklahoma Geology Notes*, vol. 12, no. 3, 2012.

The Oklahoma Geological Survey obtained grant funding from the U.S. Department of Energy to compile and digitize geothermal data for the state of Oklahoma as well as to obtain a limited amount of new data. This funding is part of the State Geothermal Data project (http://www.stategeothermaldata.org), which is organized by the Association of American State Geologists and whose goal is to *"bring data from all 50 states into the National Geothermal Data System."* In Oklahoma, one aspect of this geothermal project involves compiling old and obtaining new heat production data. Previous geothermal investigations in Oklahoma include Harrison et al. (1983), Luza et al. (1984), Lee et al. (1994), and Carter et al. (1998).

What is Heat Production?

Heat production in the earth is a measure of how much heat is released by the radioactive decay of elements such as uranium (U), thorium (Th), and potassium (K). In igneous rocks, heat production generally decreases from felsic to ultramafic rocks (Wollenberg and Smith, 1987). For example, heat production for felsic, intermediate, mafic, and ultramafic igneous rocks is ~4 microwatts per cubic meter (μWm^{-3}); ~2 μWm^{-3}; ~1 μWm^{-3}; and 0.3 μWm^{-3}, respectively. Peralkaline (low aluminum; high sodium and potassium) intrusive igneous rocks may have heat production values as high as 12 to 20 μWm^{-3}. Siliciclastic sedimentary rocks commonly have higher heat production values (2 to 4 μWm^{-3}) than do chemical sedimentary rocks (0.4 to 2 μWm^{-3}). Of the siliciclastic sedimentary rocks, shales generally have the highest heat production because they have high clay and thus high K contents.

Knowledge of heat production in igneous rocks is important because they make up large volumes of the crust. However, large volumes of sedimentary rocks occurring in deep sedimentary basins (e.g., Anadarko and Arkoma Basins in Oklahoma) can also be a factor in evaluating overall heat production.

Why Do We Measure Heat Production?

Knowledge of heat production is important in order to evaluate the state's potential for economic sources of geothermal energy using new technologies called enhanced geothermal systems that are currently being developed. Such technologies attempt to harness heat by methods such as circulating cold water into hot dry rock (HDR) rather than rely on traditional sources of geothermal energy such as hot springs.

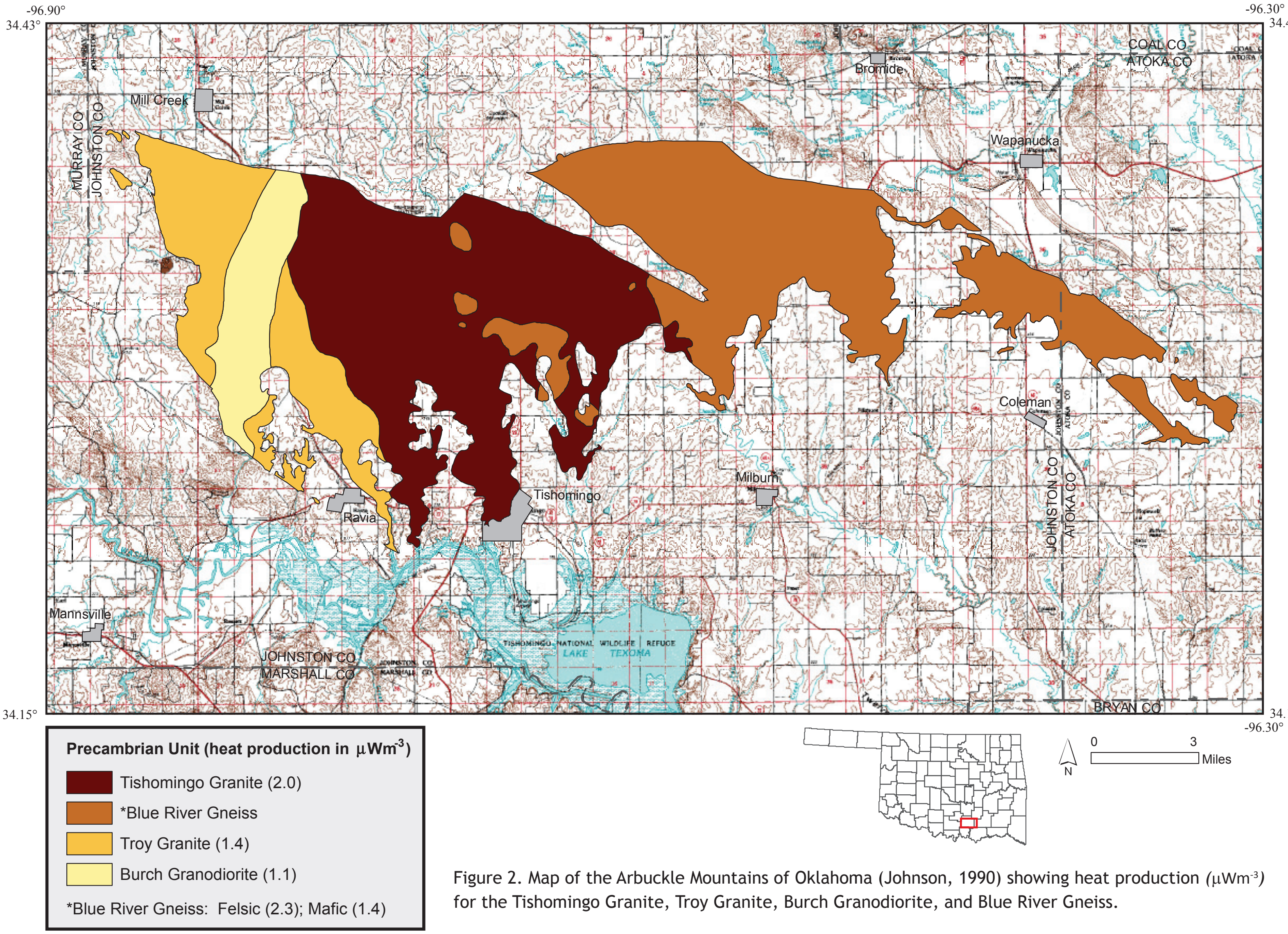

Figure 2. Map of the Arbuckle Mountains of Oklahoma (Johnson, 1990) showing heat production (μWm^{-3}) for the Tishomingo Granite, Troy Granite, Burch Granodiorite, and Blue River Gneiss.

Old Heat Production Data in Oklahoma

Heat production measurements have been obtained and estimates made for Oklahoma by Roy et al. (1968), Borel (1995), Lee et al. (1996), and Cranganu (1997). Roy et al. (1968) report a single measurement from Spavinaw Granite from northeastern Oklahoma, calculated using U, Th, and K contents. Borel (1995) reports four measurements from granite and rhyolite core. Lee et al. (1996) and Cranganu (1997) report 17 and 27 heat production estimates, respectively, calculated using gamma-ray data. Thus, 49 heat production measurements and estimates have been reported for the state of Oklahoma. These values span a wide geographic and petrographic range (Figure 1). The 49 values give an average heat production for basement rocks in Oklahoma of 2.48 μWm^{-3} (Cranganu et al., 1998).

New Heat Production Data in Oklahoma

Heat Production Determined Using a Passive Gamma-Ray System

Six samples were crushed and sent to Dr. Paul Morgan at the Colorado Geological Survey to obtain heat production measurements. However, due to the recent reorganization of the Colorado Geological Survey, results of these analyses are on hold.

Dr. Morgan's laboratory utilizes a fully shielded passive gamma-ray system to measure U, Th, and K using a doped 15-cm-diameter by 10-cm-thick sodium iodide (NaI) crystal, optically coupled to a photomultiplier tube with a 1024 pulse-height analyzer. The system is calibrated with U, Th, and K standards, diluted in olivine sand, at concentrations similar to the range typically found in rocks (non-ore bodies). Plexiglass sample containers, 15 cm in diameter by 2.5 cm thick, hold about 0.9 kg of sample, crushed to 0.2- to 0.3-cm fragments (Paul Morgan, personal communication, 2012).

Samples include (1) Troy Granite, collected from the Martin-Marietta quarry at Mill Creek in the eastern Arbuckle Mountains (1,368 ± 3 Ma; Rohs, 2001); (2) basalt dike, collected from the Martin-Marietta quarry at Mill Creek in the eastern Arbuckle Mountains (likely Cambrian or Precambrian); (3) Colbert Rhyolite, collected at the Hanson-Davis quarry in the western Arbuckle Mountains (536 ± 5 Ma; 539 ± 5 Ma; Thomas et al., 2000); (4) basalt dike, collected from the Hanson-Davis quarry in the western Arbuckle Mountains (likely Cambrian); (5) Wichita Granite from the Wichita Mountains (530 ± 1 Ma; 533 ± 1 Ma; Wright et al., 1996); and (6) gabbro from the Glen Mountains Layered Complex in the Wichita Mountains (528 ± 29 Ma; Lambert et al., 1988).

Table 1. Geochemical and heat production values for Precambrian igneous and metamorphic rocks from the Arbuckle Mountains.

Rock	Author	K (wt%)	Th (ppm)	U (ppm)	*Heat Production (μWm^{-3})
Blue River Granodiorite Gneiss (Mafic)	Lidiak & Denison (1999)	1.78	7.2	2.2	1.2
Blue River Granite Gneiss (Felsic)	Lidiak & Denison (1999)	3.88	19.5	2.3	2.3
Burch Granodiorite	Lidiak & Denison (1999)	1.83	5.3	1.9	1.0
Troy Granite	Lidiak & Denison (1999)	3.66	9.6	1.7	1.4
Granodiorite #9 (Burch)	Maniar (1987)	1.53	3.90	2.70	1.1
Granodiorite P-6A (Burch)	Maniar (1987)	1.53	3.10	1.10	0.6
Granodiorite P-15A (Burch)	Maniar (1987)	1.83	5.80	2.20	1.1
Granodiorite UN-1 (Burch)	Maniar (1987)	2.06	5.90	1.90	1.1
Granodiorite P-22A (Burch)	Maniar (1987)	2.22	10.00	3.30	1.7
Granodiorite P-10A (Burch)	Maniar (1987)	2.59	7.10	2.10	1.3
Troy #11	Maniar (1987)	3.39	7.40	1.80	1.3
Troy P-1A	Maniar (1987)	3.35	5.30	2.10	1.2
Troy P-26A	Maniar (1987)	3.36	9.00	1.50	1.3
Troy P-39-A	Maniar (1987)	4.04	13.00	1.70	1.7
Troy P-34A	Maniar (1987)	3.72	9.80	1.20	1.3
Troy P-11A	Maniar (1987)	3.86	16.00	2.60	2.1
Troy P-12A	Maniar (1987)	4.10	5.20	1.20	1.0
Troy P-24A	Maniar (1987)	3.47	11.00	1.30	1.4
Tishomingo P-85A	Maniar (1987)	3.73	10.00	3.10	1.8
Tishomingo P-45A2	Maniar (1987)	3.76	19.00	2.10	2.2
Tishomingo P-79A	Maniar (1987)	4.68	4.70	2.30	1.3
Tishomingo P-77A	Maniar (1987)	4.76	13.00	2.30	1.9
Tishomingo P-68A	Maniar (1987)	4.00	19.00	3.30	2.5
Tishomingo P-87A	Maniar (1987)	3.45	17.00	2.90	2.2
Tishomingo P-72A	Maniar (1987)	4.17	5.80	3.20	1.6
Tishomingo P-40A	Maniar (1987)	4.62	8.60	4.10	2.1
Blue River Felsic M-4A	Maniar (1987)	3.98	18.00	4.20	2.7
Blue River Felsic M-8A	Maniar (1987)	3.90	21.00	4.40	2.9
Blue River Felsic M-6A	Maniar (1987)	3.75	6.30	1.90	1.3
Blue River Mafic M-6B	Maniar (1987)	1.80	3.40	2.00	0.9
Blue River Mafic M-7A	Maniar (1987)	1.74	11.00	4.30	2.0

*The method for calculation of heat production is discussed in the text.

Table 2. Average geochemical and heat production values for Precambrian igneous and metamorphic rocks from the Arbuckle Mountains. Geochemical data are from Maniar (1987) and Lidiak and Denison (1999).

Rock	**n*	K (wt%)	Th (ppm)	U (ppm)	**Heat Production (μWm^{-3})
Blue River Granite Gneiss (Felsic)	4	3.88	16.2	3.2	2.3
Tishomingo Granite	8	4.15	12.1	2.9	2.0
Troy Granite	9	3.66	9.6	1.7	1.4
Blue River Granodiorite Gneiss (Mafic)	3	1.77	7.2	2.8	1.4
Burch Granodiorite	7	1.94	5.9	2.2	1.1

*n = number of measurements averaged for resulting heat production value.

**The method for calculation of heat production is discussed in the text.

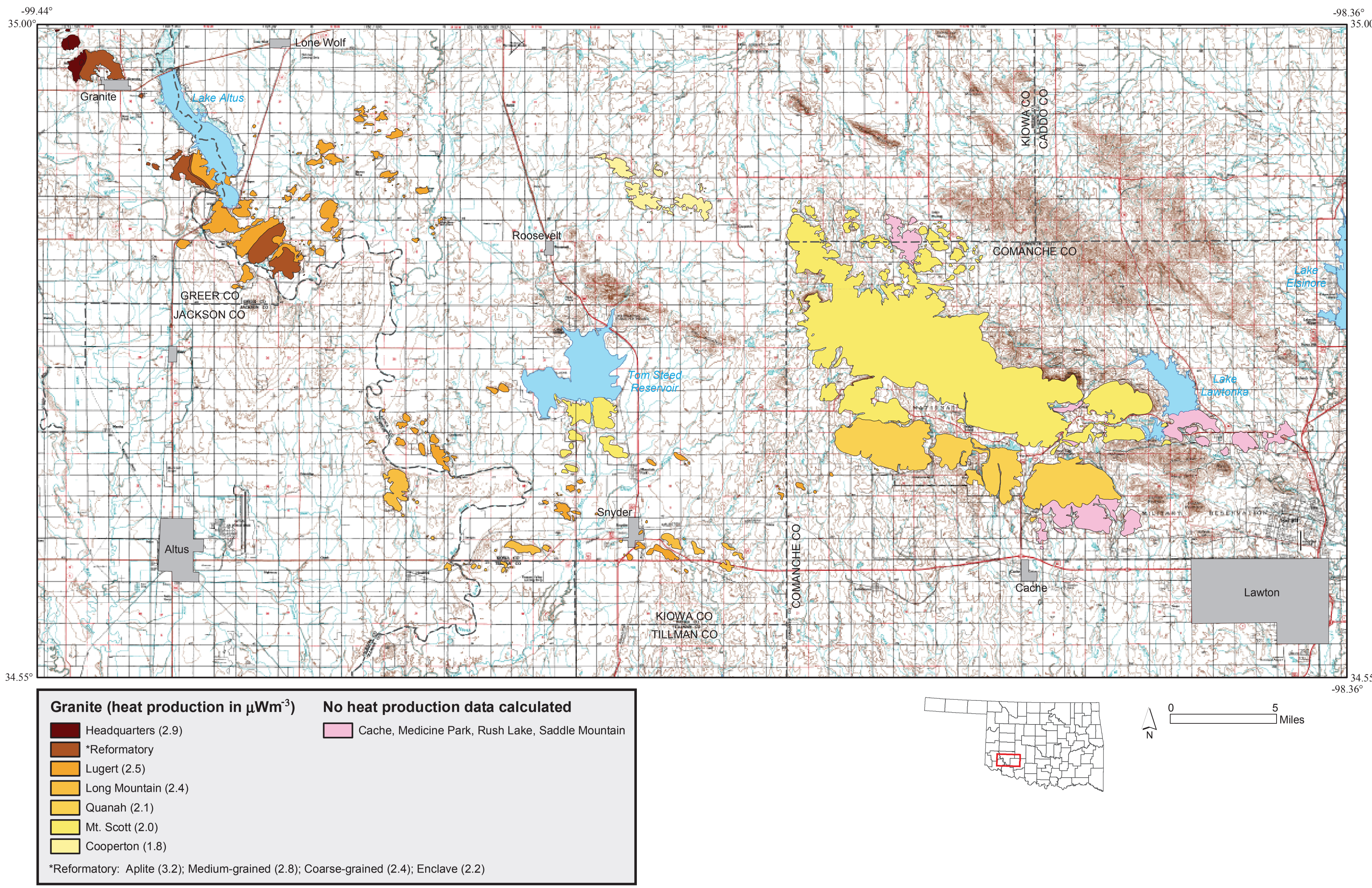

Figure 3. Map of the Wichita Mountains of Oklahoma (Stanley and Miller, 2004; Stanley and Miller, 2005) showing heat production (µWm^{-3}) for granites of the Wichita Granite Group.

Table 3. Heat production values for Cambrian granites from the Wichita Mountains. Data used for the heat production calculation are from Weaver & Gilbert (1986) and Barry Weaver, unpublished data.

*Pluton	Sample	**Heat Production (μWm^{-3})
Cooperton	W012	1.7
Cooperton	W7132	1.8
Headquarters	JH-12-90	3.3
Headquarters	JH-18-90	2.5
Long Mountain	W9102A	2.5
Long Mountain	W9101B	1.6
Long Mountain	W936C	2.0
Long Mountain	LMGG2	2.5
Long Mountain	LMGR5	2.6
Long Mountain	LMGR1	2.6
Long Mountain	LMGR7	2.4
Long Mountain	LMGG3	2.6
Long Mountain	LMGDH1	2.6
Lugert	JH-28-90	2.4
Lugert	JH-29-90	2.6
Lugert	JH-30-90	2.3
Lugert	JH-21-90	2.5
Lugert	W936B	2.5
Lugert	W7186A	1.9
Lugert	W7136	3.3
Mount Scott	W998	2.1
Mount Scott	W7248	2.1
Mount Scott	W78	2.0
Mount Scott	SQ-1	2.1
Quanah	W984	2.1
Reformatory Aplite	JH-17A-90	3.2
Reformatory Enclave	JH-6-90	2.2
Reformatory Coarse	JH-10-90	2.8
Reformatory Coarse	JH-4-90	2.0
Reformatory Coarse	JH-9-90	2.7
Reformatory Coarse	JH-7-90	2.2
Reformatory Medium	JH-17-90	2.8
Reformatory Medium	JH-15-90	2.8

*Reformatory Aplite = aplite from Reformatory Granite;
Reformatory Enclave = enclave from Reformatory Granite;
Reformatory Coarse = coarse-grained Reformatory Granite;
Reformatory Medium = medium-grained Reformatory Granite.
**The method for calculation of heat production is discussed in the text.

Heat Production Calculated Using Compiled Geochemical Analyses

Heat Production can be calculated for rocks using their density as well as their U, Th, and K concentrations, which are typically determined by X-ray fluorescence (XRF), neutron activation analysis (NAA), or inductively-coupled plasma-mass spectrometry (ICP-MS) methods. For this study, existing geochemical analyses were compiled for Precambrian igneous and metamorphic rocks from the Arbuckle Mountains and for Cambrian igneous rocks from the Wichita Mountains. For samples with U, Th, and K concentrations available, the equation $A = 10^{-5} \rho(9.52C_U)+(2.56C_{Th})+(3.48C_K)$ was used to estimate heat production, where A is heat production; ρ is the density of the rock in kgm^{-3}; C_U is the uranium concentration in ppm; C_{Th} is the thorium concentration in ppm; and C_K is the potassium concentration in weight% (Rybach, 1986). A density of 2670 kgm^{-3} was assumed (Lewis and Bentkowski, 1988). Heat production values were calculated for 31 samples from the Arbuckle Mountains and 33 samples from the Wichita Mountains. The range of heat production values calculated for the Arbuckle Mountains samples is 0.6 to 2.9 μWm^{-3}, and the average is 1.6 μWm^{-3} (Figure 2; Table 1; Table 2). The range of heat production values calculated for the Wichita Mountains samples is 1.6 to 3.3 μWm^{-3}, and the average is 2.4 μWm^{-3} (Figure 3; Table 3; Table 4). The average for all samples is 2.0 μWm^{-3}.

Table 4. Average heat production values for Cambrian granites from the Wichita Mountains. Data used for the heat production calculation are from Weaver & Gilbert (1986) and Barry Weaver, unpublished data.

*Pluton	***n*	Heat Production (μWm^{-3})
Reformatory Aplite	1	3.2
Headquarters	2	2.9
Reformatory Medium	2	2.8
Lugert	7	2.5
Reformatory Coarse	4	2.4
Long Mountain	9	2.4
Reformatory Enclave	1	2.2
Quanah	1	2.1
Mount Scott	4	2.0
Cooperton	2	1.8

*Reformatory Aplite = aplite from Reformatory Granite;
Reformatory Medium = medium-grained Reformatory Granite;
Reformatory Coarse = coarse-grained Reformatory Granite;
Reformatory Enclave = enclave from Reformatory Granite
***n* = number of measurements averaged for resulting heat production value.

Heat Production Calculated Using Data from a Gamma-Ray Scanner

Heat production can be calculated using data obtained from gamma-ray logs or gamma-ray core scanners. Gamma-ray logging involves obtaining K, U, Th, and density information for a rock in a borehole (in situ). Gamma-ray core scanners analyze rocks that have been cored and recovered from individual wells.

For this study, a Core Lab Spectral Gamma Logger Model SGL-300 from the Oklahoma Geological Survey's Oklahoma Petroleum Information Center (OPIC) was used to estimate heat production of cores using the equation $A = 0.0158 (\gamma-0.8)$, where A is heat production and γ is total gamma-ray intensity in API units (Bücker and Rybach, 1996). Twenty-one cores from the sedimentary section in Oklahoma were analyzed for this study. The rock cores are variable in lithology (sandstone, carbonate, and mixed sedimentary) and age (between Silurian and Pennsylvanian). Gamma-ray measurements were taken at multiple depths within each core. The average of the measurements for each core was used in the heat production calculation.

Heat production values for the sedimentary cores range from 0.1 to 4.2 μWm^{-3} and have an average of 0.7 μWm^{-3} (Figure 4; Table 5). The highest heat production value of 4.2 μWm^{-3} is appreciably higher than the remaining 20 values, with the second highest value being 1.4 μWm^{-3}. The highest value is from the Devonian-Mississippian Woodford Shale in Wagoner County, and the second highest value is from Granite Wash in Roger Mills County. The lowest values are from carbonate-dominated Mississippian formations. In general, cores containing mixed sedimentary rocks and sandstones have higher heat production values than cores dominated by carbonate rocks.

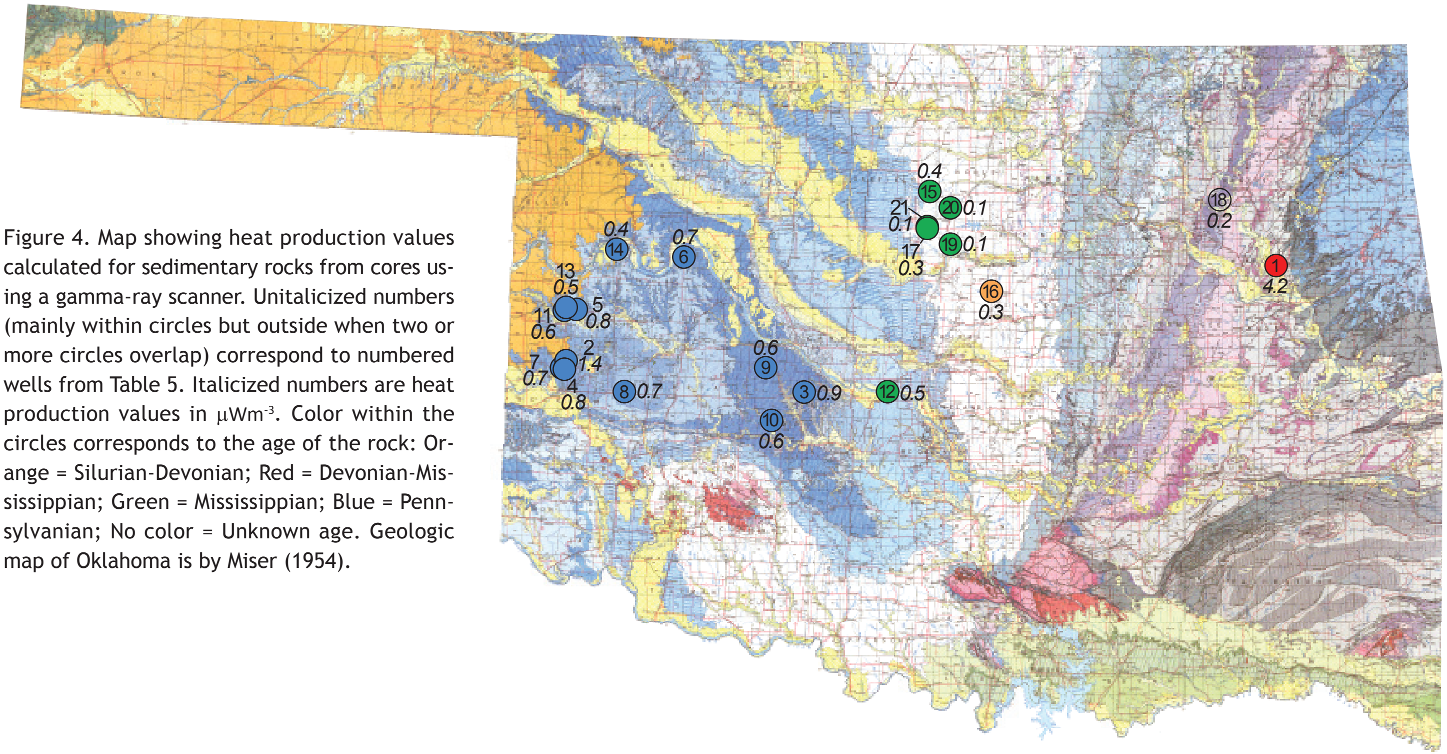

Figure 4. Map showing heat production values calculated for sedimentary rocks from cores using a gamma-ray scanner. Unitalicized numbers (mainly within circles but outside when two or more circles overlap) correspond to numbered wells from Table 5. Italicized numbers are heat production values in μWm^{-3}. Color within the circles corresponds to the age of the rock: Orange = Silurian-Devonian; Red = Devonian-Mississippian; Green = Mississippian; Blue = Pennsylvanian; No color = Unknown age. Geologic map of Oklahoma is by Miser (1954).

Discussion

Heat production measurements for Precambrian and Cambrian rocks calculated in this study using published and unpublished U, Th, K data match closely with those reported by Cranganu et al. (1998).

Heat production values for the 31 Arbuckle Mountains samples from this study range from 0.6 to 2.9 μWm^{-3}, with an average of 1.6 μWm^{-3}. In comparison, heat production values for five eastern Arbuckle granite samples reported by Cranganu et al. (1998) are between 1.1 and 2.6 μWm^{-3}, with an average of 2.0 ± 0.57 μWm^{-3}.

In this study, heat production values for 33 Wichita granite samples range from 1.6 to 3.3 μWm^{-3}, with an average of 2.4 μWm^{-3}. Similarly, heat production values for three Wichita granite samples reported by Cranganu et al. (1998) are between 1.8 and 2.6 μWm^{-3}, with an average of 2.1 ± 0.36 μWm^{-3}.

The average heat production for the 64 Wichita and Arbuckle Mountains samples from this study is 2.0 μWm^{-3}. This is the same average value calculated for eight Wichita granite and eastern Arbuckle granite samples reported by Cranganu et al. (1998).

Table 5. Heat production values calculated using gamma-ray intensity data obtained from a Core Lab Spectral Gamma Logger.

	API Number of Well	Lease, Well Number	Operator	County	Latitude (degrees)	Longitude (degrees)	Lithology	Formation	[1]n	[2]Avg GR intensity (API)	[3]A (μWm^{-3})
1	35145229490000	Dunkin, 18-11R	RDT	Wagoner	35.94743	-95.42238	Predominantly shale	Woodford	305	267.47	4.2
2	35129212820000	Nellie May, 1-8	Hadson	Roger Mills	35.43989	-99.65057	Variable	Granite Wash	732	90.18	1.4
3	35015205660000	Courtney, 1	H & Payne	Caddo	35.32477	-98.22987	Sandstone	Marchand	444	60.13	0.9
4	35009207210000	Mackey, 1-29	Valero	Beckham	35.39629	-99.65946	Mixed sedimentary	Virgil	462	51.11	0.8
5	35129204210000	Summers, 1-13	Woods Petr	Roger Mills	35.68594	-99.60153	Mixed sedimentary	Marmaton	510	50.94	0.8
6	35043200960000	Clark Unit, A-1	Wessely Petr	Dewey	35.95486	-98.97073	Sandstone	Red Fork	1548	45.62	0.7
7	35009207920000	Barnett, 2-30	Wacker Oil	Beckham	35.40351	-99.67618	Mixed sedimentary	Virgil	1482	43.32	0.7
8	35149300090000	Finnell, 1-34	GHK	Washita	35.30121	-99.29806	Mixed sedimentary	Des Moinesian	1428	42.35	0.7
9	35015204200000	Buell - State, 1	Apexco	Caddo	35.43677	-98.46242	Sandstone	Marchand	588	41.06	0.6
10	35015203020000	Betty Long, 1	Marathon	Caddo	35.18496	-98.42104	Sandstone	Marchand	189	40.25	0.6
11	35129218660000	Chalfant, 1-20	Sanguine	Roger Mills	35.68025	-99.67197	Mixed sedimentary	Marmaton	507	39.42	0.6
12	35017225520000	Payne, 1	Petrolia	Canadian	35.33552	-97.73524	Predominantly carbonate	Mississippian	857	34.03	0.5
13	35129207130000	Bailey, 1	El Paso	Roger Mills	35.69296	-99.66334	Mixed sedimentary	Marmaton	549	29.35	0.5
14	35043207100000	Craig, 1-6	McCulloch	Dewey	35.97853	-99.37203	Sandstone	Tonkawa	1621	26.71	0.4
15	35047003490000	Richard Chelf, 1	Shell	Garfield	36.29483	-97.50351	Predominantly carbonate	Mississippian	2736	25.87	0.4
16	35081236180000	Harper, 1	New Dominion	Lincoln	35.81998	-97.12539	Carbonate	Hunton	727	19.83	0.3
17	35083005760000	Oldenberg, 1-16	Shell	Logan	36.11782	-97.51653	Predominantly carbonate	Mississippian	1496	18.61	0.3
18	35131242610000	Shads, 4	Amoco	Rogers	36.26596	-95.75920	Unknown	Unknown	591	14.48	0.2
19	35083005780000	Klinger, 1	Shell	Logan	36.04512	-97.37363	Predominantly carbonate	Mississippian	3018	9.32	0.1
20	35103214130000	Tubbs, 3	Double Eagle	Noble	36.21805	-97.37933	Predominantly carbonate	Mississippian	867	8.28	0.1
21	35083501180000	Sutton, 1	Shell	Logan	36.12639	-97.51692	Predominantly carbonate	Mississippian	1028	7.93	0.1

[1]n = number of measurements averaged to calcuate heat production value.

[2]Avg GR intensity = average gamma-ray intensity.

[3]A = heat production; method for calculation of heat production is discussed in the text.

Conclusion

The new data presented in this study provides a solid understanding of the heat production generated from Precambrian igneous and metamorphic rocks from the Arbuckle Mountains and from Cambrian granites from the Wichita Mountains in Oklahoma. The data greatly enhance our knowledge of Oklahoma's geothermal resource potential and have been submitted to the State Geothermal Data project. These data, as well as all geothermal information compiled for the state of Oklahoma, is available to the public at the National Geothermal Data System website (http://geothermaldata.org). Additional heat production information will be reported as new data become available.

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2013 in Review — Oklahoma Geological Survey

G. Randy Keller, Oklahoma State Geologist, and Connie Smith, OGS Public Information Officer

G. Randy Keller, Oklahoma State Geologist

The Oklahoma Geological Survey (OGS) had a very productive year in 2013. The research area that took front stage, however, dealt with Oklahoma's seismic activity. Oklahoma again experienced increasing activity and public interest in earthquakes. Seismologists were kept busy locating and assigning magnitudes to the events and responding to questions from the public, other government agencies, the energy industry and, of course, the media. The staff went to great lengths to provide accurate and unbiased scientific findings in an effort to get correct information to the public and counteract the misinformation surrounding earthquakes in Oklahoma.

Public Service and Outreach

One of the most important programs at the OGS is public service. It is a daily activity that encompasses everything from phone calls and e-mails to presentations before various scout, educational, and civic groups. It could be in the form of a classroom visit, a field trip, or rock identification for someone who walked in unannounced.

In 2013 the Survey participated in its fifth edition of the *Oklahoman's* Newspapers in Education program that supplies 25 copies of a 16-page workbook, six additional lessons, and numerous activities to classrooms across the state. This year's edition was authored by Survey geologist Dr. Neil Suneson, and the topic was *OKLAHOMA ROCKS! State Parks*. Teachers can sign up for the series free of charge, and the workbooks are supplied in paper copies with additional materials and the teacher guidebook online. In addition, there are six related one-quarter-page lessons that run in the *Oklahoman*, giving wide readership to some interesting and thought-provoking points about the state's geology, its uniqueness, and its impact on the Oklahoma economy. This year's publication and other OGS contributions can be accessed online at: http://nie.newsok.com/educators/curriculum/.

As another educational effort, the Survey builds and maintains rock and mineral kits for Oklahoma earth science teachers. Several kits were sent out to Oklahoma science teachers in 2013, including some who lost classroom material in tornadoes.

The OGS provides speakers and materials for various academic, civic, and scout organizations, classrooms, and town-hall meetings, and participates in events such as Water Day and GIS Day at the Capitol; Science Fest (which is held annually at the Oklahoma City Zoo — *see photo on page 13*); and Science in Action Day at the Sam Noble Oklahoma Museum of Natural History on the OU Norman campus.

Survey industrial geologist Dr. Stanley T. Krukowski worked with the Society of Mining, Metallurgy and Exploration, Inc., serving on the Merit Badge Development and Launch Team to establish the Mining in Society merit badge for the Boy Scouts of America .

Dr. Suneson and fellow Survey geologist Richard Andrews are again co-teaching a course for the ConocoPhillips School of Geology & Geophysics (CPSGG) at OU, which is Geology 4233: Subsurface Methods. This is an upper lever course emphasizing reservoir engineering, volumetric calculations, unconventional reservoir analyses, interpretation of new field studies, well log interpretation, formation evaluation, and subsurface mapping. Dr. Suneson also is working with Red Earth Desk and Derrick Club of Oklahoma City to create interpretive signs about the geology along Burford Lake Trail in the Wichita Mountains National Wildlife Refuge, and the OGS will publish a new guidebook to southwestern Oklahoma's Wichita Mountains in the spring of 2014.

Seismic Studies

During 2013 earthquakes in Oklahoma again occurred at record levels and consumed a large amount of OGS staff time and effort. Much of the effort focuses not only on recording and analyzing the latest earthquakes, but evaluating events as they relate to the issue of induced seismicity. While it is well understood that earthquakes can be triggered by fluid injection, it is also well documented that Oklahoma is a known site for active seismicity within the midcontinent. During 2013, the Survey recorded and located some 2,847 local earthquakes in Oklahoma, with 222 of these reported felt. These quakes and their sources are under great scrutiny at the OGS; plans for 2014 include the addition of staff and and acquisition of more monitoring equipment.

In 2013, the OGS brought a number of seismic stations up to date and also installed one semi-continuous station and one permanent station. Eleven OGS temporary seismic stations were operated at different sites, and additional temporary USGS stations were installed and supported. Survey seismolo-

Oklahoma Geological Survey Mission Statement:

The Oklahoma Geological Survey is a state agency for research and public service located on the Norman Campus of the University of Oklahoma and affiliated with the University of Oklahoma Mewbourne College of Earth and Energy. The Survey is chartered in the Oklahoma Constitution and is charged with investigating the state's land, water, mineral, and energy resources and disseminating the results of those investigations to promote the wise use of Oklahoma's natural resources consistent with sound environmental practices. The Survey is not a regulatory agency.

gist Austin A. Holland also supervised and mentored one undergraduate student and two graduate students, all of whom received a great deal of practical experience.

The OGS provides information to federal (USGS, Army Corp of Engineers and EPA), as well as state and local officials about specific earthquakes, earthquake issues, and earthquake hazards, and works closely with the Oklahoma Corporation Commission on the specifics of induced seismicity and drilling activities. Holland participated in two USGS Powell Center Workgroup meetings on induced seismicity and spoke to many local, state, and national scientific groups.

Holland and OGS Director Dr. G. Randy Keller were involved in a multitude of media interviews locally, nationally, and internationally seeking to explain earthquakes in general, induced seismicity, and regional seismicity. Holland also presented many talks and town hall meetings on earthquake hazards and recent earthquake activity to different civic groups throughout Oklahoma. He initiated many of the meetings and tried when at all possible to address the concerns of citizens and town and city officials. He has made himself and his cell phone number available and answers calls on a 24/7 basis when needed. Even with his duties as OGS director and teaching obligations, Dr. Keller continues to respond to interview requests and reassure the public that Survey information reflects our latest findings and is made available.

In response to concerns that oil and gas industry operations (specifically, injection of drilling waste and production fluids into the ground) can be a cause of earthquakes, the Survey sponsored a workshop on Fluid Injection Induced Seismicity on July 16, 2013. The participants in the workshop represented interested parties such as environmental groups, state agencies, non-governmental organizations, and oil and gas operators. This gathering and exchange of ideas was the first step toward developing a set of recommended best practices to address the issue of induced seismicity. While some earthquakes can be associated with drilling and injection activity, focus also must be on the fact that not all of the increased activity since 2010 can be related to human activities. The findings are passed along to the Oklahoma Corporation Commission, since the Survey is not a regulatory agency.

OGS Industrial Minerals Geologist Stan Krukowski teaches Oklahoma elementary school students "Birdseed Mining" at Science Fest, held at the Oklahoma City Zoo.

Even though the risk of damaging induced earthquakes appears to be small, that risk can be mitigated by appropriate industry practices consistent with the current understanding of the science. Attendees at the workshop discussed a possible set of best practices, and the OGS will take into consideration the comments and concerns expressed and, in continuing consultation with all participants, will ultimately develop a draft set of recommended best practices. These best practices are intended to provide guidelines primarily to the oil and gas industry concerning wastewater disposal wells, but may be applicable in many other cases of fluid injection. Once developed, the draft recommended best practices will be made available for public comment.

Energy Investigations

When Brian Cardott joined the Oklahoma Geological Survey in 1981 as an organic petrologist looking at oil and gas source rocks and coal, his first project was to measure the vitrinite reflectance of the Woodford Shale in the Anadarko Basin. Vitrinite, derived from woody organic matter of post-Silurian-age rocks, is used to determine the thermal maturity (from the maximum temperature attained) of the rock http://www.searchanddiscovery.com/pdfz/documents/2012/40928cardott/ndx_cardott.pdf.html. Even though thermal maturity is one of the most important parameters used in the evaluation of gas-shale and shale-oil plays, at the time of these studies, it wasn't imagined that it would come to play the role it has in energy exploration.

Vitrinite reflectance (VR_o) is a commonly used thermal maturity indicator. Many operators use the vitrinite-reflectance value without knowing what it is or how it is derived. Thermal maturity, along with the organic matter type (e.g., oil or gas generative) and quantity, is used to estimate the type of hydrocarbon generated. All oil or gas reservoirs require a mature hydrocarbon source rock as the source of produced hydrocarbons. Since the Woodford Shale is an important hydrocarbon source rock and was deposited prior to the Pennsylvanian orogenies, Cardott has measured the vitrinite reflectance of the Woodford Shale across the state. Based on this work, the thermal maturity of the Woodford Shale is known in much of Oklahoma, with the highest recorded vitrinite reflectance in Oklahoma of 6.36% VR_o in the Arkoma Basin.

Cardott's bibliographies, papers, and data are some of the most accessed pages on the OGS website: http://ogs.ou.edu/level2-energy.php.

OGS Energy-Related Workshops and Field Trips

37th Annual Western Interior Coal Forum – June 4-5, 2013 – 12 Attendees

Fluid Injection Induced Seismicity Workshop – July 16, 2013 – 73 Attendees

Oklahoma Shale Gas & Oil Workshop – November 20, 2013 – 203 Attendees

Oklahoma Shale Gas & Oil Field Trip – November 19, 2013 – 30 Attendees

Oklahoma Shale Gas & Oil Field Trip – November 21, 2013 – 34 Attendees

Basic Geological Studies

Geothermal

National Geothermal Data System project in cooperation with AASG: This is an ongoing three year project that began in July 2010 and was completed in 2013. The project includes creating and managing database(s), document scanning, and completing several data sheets. Specific data transfers (deliverables) are completed using pre-arranged templates that are extremely elaborate and require constant revisions.

Helium

Survey geologist Dr. Julie Chang has been investigating helium and compiled a bibliography of helium references for Oklahoma and other localities, and produced a map in ArcMap 10.0 of helium contents for natural gas wells in Oklahoma and surrounding states. She is also writing articles about helium in Oklahoma for the Oklahoma City Geological Society's *Shale Shaker* and the *Oklahoma Geology Notes*.

Field Trips

Members of the Survey staff also planned and led many field trips throughout the state in 2013. Some are associated with meetings and workshops, whereas others are for various professional or educational groups. An example of the more unusual topics was cement company exploration efforts for raw materials in Oklahoma and north Texas.

Mining and Minerals

Dr. Krukowski keeps track of Oklahoma's mineral resources, leads field trips, and works with various professional groups and companies within the state. His research projects include contributing to the Directory of Oklahoma Mines and investigating industrial minerals utilization by Native Americans.

Other

Dr. Keller, along with OGS research staff members Dr. Kevin Crain and Dr. Vikram Jayaram continue to study the deep structure of Oklahoma and surrounding areas for their 3-D geophysical models. This is part of an NSF funded project on the mid-continent rift.

The OGS is working on new integrated studies made along the Ouachita orogenic belt. This work is based on industry 3-D seismic data from that area.

Another very useful project taken on by Survey geologist Brittany Pritchett involves going through field guides and picking out the locations of the stops, cataloging what the stops were viewing (formations, uncommon minerals, fossils, etc.), and then putting this information in Google Earth. The ultimate goal is to create an interactive map on the OGS website where one could search by field guide and see the location of the stops, or search by geological formation and access every field guide/stop that includes that particular formation and locating it.

Pritchett is also updating the oil and gas field map (GM 36) that was published 10 years ago, addressing the problems of part of the Pennsylvanian stratigraphy (Krebs through Skiatook Group) in Oklahoma. She is trying to reconcile rock formations called different names or used as Group, Formation, or Member interchangeably. She also spends time working with graduate students in the CPSGG's Devon X-Ray Diffraction Lab.

Oklahoma Petroleum Information Center (OPIC)

OPIC is a 200,000 sq. ft. facility used by many individuals and groups, along with many patrons from the energy industry seeking a variety of information. Labs are held there for OU geology students, and groups of teachers come for tours and special teaching sessions. Many people associated with state and federal agencies also make use of the massive core and sample collections, paper data records, and aerial photos housed here: http://ogs.ou.edu/level2-OPIC.php.

The number of boxes of cores pulled increased from 12,036 in 2011; to 13,412 in 2012; to a new record of 15,758 in 2013.

Donations Received and Logged In for 2013:

- Core: 45 wells/912 boxes
- Cuttings: 700 wells/1754 boxes
- Shawnee: (log in only) 293 wells/488 boxes

Mapping and Cartography

The STATEMAP program, with Dr. Tom Stanley and Dr. Julie Chang, is currently in its 17th year. To date, more than 42 detailed 7.5' geologic maps at 1:24,000 scale and 16 reconnaissance maps at 1:100,000 scale are complete and available on the website (www.ogs.ou.edu) and in hard copy and digital format upon request.

Now that mapping of the Tulsa Metro Area is completed, detailed, 1:24,000 mapping has shifted focus to mapping of the Vanoss Quadrangle within the Ada area.

The northwest to southeast sweep across the state with the reconnaissance-mapping program continues. The conjoined Tishomingo-Sherman 1-degree sheet should be available to the public later in the year.

Dr. Stanley also serves as an Adjunct Professor for the CPSGG and teaches the department's Geology Field Camp in Canon City, Colorado.

Field trip stop on the Oklahoma Shale Gas and Oil Field Trip. Participants examining exposure of bitumen-filled fractures in Woodford Shale middle member in McAlister Cemetery Quarry.

Survey GIS professional Russell Standridge and geologist Dr. Julie Chang examine an outcrop near Lake Thunderbird. Photo by Jim Anderson.

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