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To Accompany

A FLUID INCLUSION TECHNIQUE FOR DETERMINING MAXIMUM TEMPERATURE IN CALCITE AND ITS COMPARISON TO THE VITRINITE REFLECTANCE GEOTHERMOMETER

by Charles E. Barker and Robert H. Goldstein

METHODS

In our samples, the fluid inclusion homogenization temperatures (Th) were measured from calcite on a Fluid Inc.-adapted, USGS-designed, gas-flow heating and freezing stage. Established stage calibration procedures (Roedder, 1984; Shepard et al., 1985) were followed. All of our samples were prepared using techniques to prevent overheating. Inclusions were heated and homogenized to liquid (overheating avoided) before freezing them for salinity measurements. We cannot assure that such precautions against altering Th were taken in the published data, however, most of the published data come from samples that reached greater than 100°C during burial, so that minor heating during sample preparation would not influence the results. The published data were not used if the sample were frozen before heating to Th (Lawler and Crawford, 1983). The Th data were not corrected for pressure.

If necessary, dispersed sedimentary organic matter (OM) in our rock samples was concentrated by crushing and sink-float isolation. Coal samples were crushed only. The crushed OM or coal was mixed with epoxy, and polished. Reflectance of the polished samples was measured using standard procedures (Stach et al., 1982; Bustin et al., 1983).

In our sample suite, we used mostly Th and Rm data from samples that were in close association with each other (ideally the same sample). In some cases, if a well-constrained value could be interpolated from adjacent sample data, the case was used. For instance, if the fluid inclusion data were the result of a regional event, in a structurally simple area, then a well constrained regional Rm or other coal rank value would be used. In structurally complex areas, only a Rm value from the same structural block as the Th data would be used. In hydrothermal deposits or vein samples which may not have been in equilibrium with the regional temperature, only a Rm value from the deposit itself would be used. In difficult samples (primarily those from Sacramento Mountains and northwest Kansas), duplicate measurements of Rm were run to assess operator bias in the data. If a difference of over 10 percent or so exists between the Rm values, then Rock-Eval pyrolysis Tmax data converted to a Rm equivalent (VRE) measure, was used to indicate the more probable Rm value by its proximity to one of the measured Rm values.

The present peak temperature from which samples were collected, Th, and/or Rm values are compiled for subsurface systems interpreted to be at peak temperature (Tpeak). The present Tpeak is computed from bottom hole temperature derived from logs, measured after equilibration of the well, or calculated using a locally determined geothermal gradient and mean surface temperature. In several cases, the bottom-hole temperatures (BHT) were approximately converted to formation temperature using the American Association of Petroleum Geologists (1976) generalized correction for North America. This correction was applied as a statistical correction (see review by Barker, 1989b) to these data to make them more conformable to the equilibrium formation temperature data usually available. Scott (1982) estimated the AAPG correction has a root mean square error of 10°C in correcting the BHT to equilibrium formation temperature.

To determine the relationship of Th to present Tpeak, we compiled the mean (Thmean), and the highest temperature mode for polymodal distributions, or the single mode for unimodal distributions (Thmode). However, both statistics were not available for some studies, so in some cases we substituted Thmean for Thmode in the regression analyses (as noted in the table).

Locality, Country, Description (Reference)	Depth (km)	Rm mean (%)	Th mean (°C)	Th mode (°C)	Th range low/high (°C)	Timing of Inclusions Relative to Tpeak	Present T if at Tpeak (°C)	Functional Heating Duration (yr)	Inclusion Petrography / Host Mineral
ACTIVE GEOTHERMAL SYSTEMS									
East Mesa, USA,									
well Mesa 6-2	1.13	1.7	196	222 [d]	165-240	near peak [b]	N/A	<10^6 [g]	Origin unknown/
(Th-Hoagland and	1.08	1.6	215	208	207-245	near peak?	N/A	<10^6	calcite veins
Elders, 1977)[g]									
(Rm-this paper)									
East Mesa, USA,									
well Mesa 31-1.	1.36	0.8	155	N/A	135-160	near peak	144	<10^6 [g]	Origin unknown/
(Th-Miller, 1980)									calcite veins
(Rm-this paper)	1.71	1.1 [n]	153	N/A	140-180	near peak	153	<10^6 [g]	as above
	1.72	1.1 [n]	147	N/A	135-175	near peak	155	<10^6 [g]	as above
	1.88	0.8	161	N/A	140-180	near peak	158	<10^6 [g]	as above
Heber, USA,	0.48	1.6	170	175 [d]	150-190	at peak	N/A	<10^6 [g]	Origin unknown
well Holtz-1.	0.79	1.8	185	190 [d]	170-200	at peak	N/A	<10^6 [g]	calcite chips
(Th-Browne, 1977)	0.92	1.7	201	200 [d]	150-225	at peak	N/A	<10^6 [g]	
(Rm-this paper)	1.22	1.9	210	220 [d]	190-225	at peak	N/A		
	1.26	1.95	196	210 [d]	175-220	at peak	N/A	<10^6 [g]	as above
	1.34	1.9	190	195 [d]	175-205	at peak	N/A	<10^6 [g]	
	1.52	2.0	215	235 [d]	180-265	at peak	N/A	<10^6 [g]	as above
Cerro Prieto, Mexico,									
well M-84.	1.28	3.2	316	N/A	300-325	early?	320 [j]	10^4 [g]	Origin unknown/
(Th-Elders et al.,									calcite chips
1978)[g]									
(Rm-Barker, 1979,	1.32	3.5	296	N/A	258-308	early?	324 [j]	10^4 [g]	as above
and this paper)	1.39	3.2	312	N/A	307-323	early?	328 [j]	10^4 [g]	as above
	1.64	3.8	324	N/A	322-327	early?	343 [j]	10^4 [g]	as above
As above, well M-9	0.9	1.6	154	154	154(n=1)	early?	234 [j]	10^4 g	as above
As above, well M-10	1.19	2.7	290	N/A	271-311	near peak	290 [j]	104 g	as above
As above, well M-51	1.56	3.7	319	N/A	N/A	near peak	327 [j]	10^4 g	as above
As above, well M-53	1.81	3.6	321	N/A	316-337	near peak	332 [j]	10^4 g	as above
As above, well M-53	1.82	3.6	350	N/A	305-375	near peak	332 [j]	10^4 g	as above
As above, well M-53	1.96	3.6	324	N/A	304-346	near peak	336 [j]	10^4 [g]	as above
As above, well M-90	1.09	1.5 [o]	274	N/A	274(n=2)	near peak	311 [j]	10^4 [g]	as above
As above, well M-90	1.15	2.0 [o]	315	N/A	312-317	near peak	312 [j]	10^4 [g]	as above
As above, well M-90	1.29	3.1 [o]	256	N/A	247-258	near peak	303 [j]	10^4 [g]	as above
As above, well M-90	1.32	3.1 [o]	280	N/A	268-286	near peak	301 [j]	10^4 [g]	as above
As above, well M-90	1.35	3.4 [o]	292	N/A	280-311	near peak	308 [j]	10^4 [g]	as above
As above, well M-91	1.37	1.3	259	N/A	254-267	near peak	322 [j]	10^4 [g]	as above
As above, well M-91	1.64	1.6	246	254	231-263	near peak	N/A	10^4 [g]	as above
As above, well M-91	1.72	1.5	271	N/A	261-303	near peak	326 [j]	10^4 [g]	as above
As above, well M-91	1.80	2.1 [n]	283	N/A	243-345	near peak	327 [j]	10^4 [g]	as above
As above, well M-94	1.30	2.2	225	N/A	148-275	near peak	---	10^4 [g]	as above

Locality, Country, Description (Reference)	Depth (km)	Rm mean (%)	Th mean (°C)	Th mode (°C)	Th range low/high (°C)	Timing of Inclusions Relative to Tpeak	Present T if at Tpeak (°C)	Functional Heating Duration (yr)	Inclusion Petrography / Host Mineral
Cerro Prieto, Mexico, well M-84, (Th-Sterner, 1985) (Rm-Barker, 1979)	1.06	2.6	242	255 [d]	220-280	early?	240 [j]	10^4 [g]	Origin unknown/ calcite cement
	1.1	3.0	300	300	290-305	early?	306 [j]	10^4 [g]	as above
	1.17	3.0	290	295 [d]	265-305	early?	312 [j]	10^4 [g]	as above
	1.19	3.2	308	305	270-310	early?	314 [j]	10^4 [g]	as above
	1.31	3.5	309	320 [d]	280-325	early?	322 [j]	10^4 [g]	as above
	1.4	3.2	320	320	310-330	early?	328 [j]	10^4 [g]	as above
	1.67	3.8	347	347	340-355	early?	345 [j]	10^4 [g]	as above
Cerro Prieto, Mexico well M-9. (Th-Sterner, 1985) (Rm-this paper)	0.68	1.3	181	203 [d]	165-215	early?	196 [j]	10^4 [g]	Origin unknown/ calcite cement
	0.83	1.55	238	238	230-245	early?	250 [j]	10^4 [g]	as above
	0.90	1.7	208	221 [d]	180-230	early?	249 [j]	10^4 [g]	as above
	1.01	2.1	260	260	255-270	early?	248 [j]	10^4 [g]	as above
	1.09	2.35	230	230	230(n=1)	early?	248 [j]		
	1.31	2.7	264	283 [d]	205-290	early?	248 [j]	10^4 [g]	as above
	1.36	2.6	241	295 [d]	185-305	early?	247 [j]	10^4 [g]	as above
Cerro Prieto, Mexico well M-94.	1.22	0.6	<u>198</u>	N/A	140-300	near peak		10^4 [g]	Origin unknown/ calcite cement
(Th-Sanford, 1981)	1.29	2.2	<u>250</u>	N/A	245-255	near peak		10^4 [g]	as above
(Rm-Barker, 1979)	1.60	2.2	<u>258</u>	N/A	225-265	near peak		10^4 [g]	as above
well T-366 (Th-Sanford, 1981) (Rm-this paper)	2.0	1.65	<u>208</u>	N/A	190-230	near peak		10^4 [g]	as above
Salton Sea, USA, well Sinclair-4. (Th and Tpeak Freckman, 1978)[g] (Rm-this paper)	1.03	2.2	255	272 [d]	227-275	near peak	238 [j]	10^4 [g]	Origin unknown/ calcite chips
	1.06	2.2	238	256 [d]	195-265	near peak	242 [j]	10^4 [g]	as above
	1.08	2.3	263	263	257-269	near peak	249 [j]	10^4 [g]	as above
	1.21	2.3	206	209	201-209	near peak	257 [j]	10^4 [g]	as above
	1.27	2.5	260	260	243-275	near peak	265 [j]	10^4 [g]	as above
	1.32	2.2	256	258	249-263	near peak	270 [j]	10^4 [g]	as above
	1.35	2.6	262	260	235-283	near peak	272 [j]	10^4 [g]	as above
	1.37	2.3	252	278	227-287	near peak	276 [j]	10^4 [g]	as above
	1.40	2.75[n]	268	274	245-290	near peak	278 [j]	10^4 [g]	as above
	1.43	2.75	278	278	275-281	near peak	279 [j]	10^4 [g]	as above
	1.44	2.8	247	248	210-269	near peak	280 [j]	10^4 [g]	as above
	1.45	2.9	263	272 [d]	255-278	near peak	281 [j]	10^4 [g]	as above
	1.51	3.0 [n]	265	266	263-271	near peak	288 [j]	10^4 [g]	as above
	1.54	3.0 [n]	276	272	263-291	near peak	291 [j]	10^4 [g]	as above
	1.58	3.0	279	282 [d]	269-285	near peak	292 [j]	10^4 [g]	as above

Locality, Country, Description (Reference)	Depth (km)	Rm mean (%)	Th mean (°C)	Th mode (°C)	Th range low/high (°C)	Timing of Inclusions Relative to Tpeak	Present T if at Tpeak (°C)	Functional Heating Duration (yr)	Inclusion Petrography / Host Mineral
Salton Sea, USA, well Magmamax-2. (Th and Tpeak-Freckman, 1978)[g] (Rm-this paper)	0.82	2.3	<u>303</u>	N/A	286-315	near peak	290 [j]	10^4 [g]	as above
Raft River, USA, well RRGE-2. (Th, Rm-this paper)	1.33	1.5	133	145	120-148	near peak	149 [j]	10^6 [g]	Primaries[a]/ vein calcite
Guaymas Basin, Gulf of California, Outcrop. (Th, Tp-Peter and Scott, 1988)	2.0	N/A	225	251	198-262	at peak	273	--	Primaries/ calcite cement
					EXTINCT GEOTHERMAL SYSTEMS				
Gaspe, Canada, Outcrop. (Duba and Williams-Jones, 1983)	0	4.6	301	300	260-360	early?	--	$<10^6$ [c]	Primaries/ vein calcite
Point Delgada, USA, Outcrop. (Blake et al., 1988) (McLauglin et al., 1985)	0	2.5	254	250	246-288	at peak [b]	--	$<10^6$ [c]	Origin Unknown/ early vein calcite
Benue Trough, Nigeria, Outcrop (Th-Nwachukwu, 1975) (VRE-Simpson, 1954; Nwachukwu, 1985)	0	0.8	N/A	103	40-240	early?	--	$2x10^6$ [f]	Various origins/ calcite vein
Fore-Sudetic Monocline, Poland, Wells. (Th-Specik and Kozlowski, 1987) (Rm-Speczik, 1988)	4.94 2.31	1.9 2.3	193? 212?	205? 220?	180-205 204-220	early? early?	-- --	-- --	Various origins/ Calcite veins

Locality, Country, Description (Reference)	Depth (km)	Rm mean (%)	Th mean (°C)	Th mode (°C)	Th range low/high (°C)	Timing of Inclusions Relative to Tpeak	Present T if at Tpeak (°C)	Functional Heating Duration (yr)	Inclusion Petrography / Host Mineral
					BURIAL DIAGENESIS				
Smackover Formation									
Mount Vernon Field,									
USA, wells.	2.40	0.6	90	80	58-136	early	94 [i]	10^6 [f]	Primaries/
(Th, Tp-Klosterman,									calcite cement
1981a, 1981b)	2.42	0.6	87	80	58-136	early	95 [i]	10^6 [f]	as above
(VRE-Claypool and	2.42	0.6	85	80	58-136	early	95 [i]	10^6 [f]	as above
Mancini, 1989;									
Nunn and									
Sassen, 1986)									
Walker Creek Field,									
USA, wells.	3.34	0.8	109	118	63-158	early	125 [i]	10^6 [f]	as above
(Th, Tp Klosterman,									
1981a, 1981b)	3.31	0.8	112	118	63-158	early	129 [i]	10^6 [f]	as above
(VRE-as above)									
Arkansas, USA,	2.41	0.6	102	N/A	N/A	early	102 [i]	10^6 [f]	as above
wildcat well.									
(Th-Moore and									
Druckman, 1981)									
(Tp-Klosterman,									
1981a, 1981b)									
(VRE-as above)									
Smackover Formation									
Texas, Arkansas, and									
Mississippi, USA,									
(Th-O'Hearn, 1984)									
(VRE, as above)									
(Tp-Nunn, 1984)									
Well names:									Primaries/
Murphy 1 Giffco	2.4	0.5	98	100	69-130	early	99 [h]	$2x10^7$ [f]	calcite cement
Lear 1 Clements	3.3	0.7	128	130	97-150	early	128 [h]	$2x10^7$ [f]	as above
Aminoil 2 Dixon	3.4	0.75	108	120	90-125	early	133 [h]	$2x10^7$ [f]	as above
Murphy 1 IPC	2.5	0.55	103	120	83-121	early	105 [h]	$2x10^7$ [f]	as above
Pennzoil 1 Taylor	3.3	0.7	128	125	111-158	early	123 [h]	$2x10^7$ [f]	as above
Texaco 1 Newsome	3.5	0.8	120	125	88-146	early	133 [h]	$3x10^7$ [f]	as above
Humble 1 Newsome	4.0	0.9	139	142	128-147	early	143 [h]	$3x10^7$ [f]	as above
Phillips 1 Josephine	5.9	1.8	129	130	122-148	early	179 [h]	$3x10^7$ [f]	as above

Locality, Country, Description (Reference)	Depth (km)	Rm mean (%)	Th mean (°C)	Th mode (°C)	Th range low/high (°C)	Timing of Inclusions Relative to Tpeak	Present T if at Tpeak (°C)	Functional Heating Duration (yr)	Inclusion Petrography / Host Mineral
Central Graben, Denmark, Oil Fields (Th-Jensenius and Monksgard, 1989) (Rm-Thomsen et al. 1983, fig. 2)									
Oil field names:									Various origins/ calcite cement
North Arne	2.23	0.55	85	85	70-110	early	95	$3x10^6$ [f]	as above
Skjold	1.6	0.5	78	80	50-110	early	82	3x106 [f]	as above
East Rosa	1.5	0.45	72	70	60-100	early	72	$3x10^6$ [f]	as above
Rolf	1.9	0.5	83	80	50-110	early	96	$3x10^6$ [f]	as above
Nils	1.9	0.5	72	80	60-100	early	68	$3x10^6$ [f]	as above
Vagn	1.54	0.45	75	80	60-105	early	65	$3x10^6$ [f]	as above
Bornholm, Denmark Outcrop. (Th-Jensenius, 1987) (Rm-Thomsen et al., 1983)	0	2.25	136	200 [d]	105-210	early	--	10^6? [f]	Various origins/ calcite vein
Denmark onshore, Wells. Orslev-1	2.1	0.65	80?	87	63-98	unknown	--	--	Primaries only
Novling-1	3.5	0.8	80?	90	63-103	unknown	--	--	Secondaries
(Th, Rm-as above)									both in calcite veins
Maracaibo Basin, Venezuela, well. (Visser, 1982)	2.73	--	84 [m]	112	50-130	at peak	157 [l]	10^6 [f]	Primaries only/ calcite veins
Haltenbanken, North Sea, Norway, well, Jurassic rocks. (Th-Saigal and Bjorlykke, 1987) (Rm-Hvoslef et al. 1988)	1.68	0.4	66	N/A	56-68	at peak?	68 [h]	10^6 [f]	Various origins/ calcite cement
North Coles Levee field, USA, wells. (Th-Boles, 1987) (Rm-Boles and Ramseyer, 1988)	2.73	0.5	59	N/A	57-62	early	107 [j]	10^6 [f]	"Very small" inclusions- Various origins/ calcite cement

Locality, Country, Description (Reference)	Depth (km)	Rm mean (%)	Th mean (°C)	Th mode (°C)	Th range low/high (°C)	Timing of Inclusions Relative to Tpeak	Present T if at Tpeak (°C)	Functional Heating Duration (yr)	Inclusion Petrography / Host Mineral
Fateh Field, Dubai wells. (Horsfield and McLimans, 1984; Videtich et al., 1988)	2.7	0.9	85	98 [d]	52-135	early	115 [i]	$5x10^6$ [f]	Primaries/ late blocky calcite spar
Winterburn Basin, Canada, well LSD-10 (Nahnybida et al., 1982)	2.3	1.0	144	150	90-200	at peak?	128 [h]	10^6? [f]	Primaries?/ calcite cement
Cottonwood Wash, Utah, USA outcrop, (Meunier et al., 1987)	0	0.6[p] (VRE)	95	107	70-195	early to at peak	--	10^6 [f]	Various origins/ calcite
Paradox basin, USA, outcrop. (Th-Morrison and Parry, 1986) (Rm-Hite et al., 1984)	0	0.65	93	98	44-122	at peak	--	10^6 [f]	Various origins/ calcite vein
Denver Basin, well Berthoud-4, USA (Crysdale and Barker, 1988)	0.91	0.6	92	93	65-95	early?	--	10^6 [f]	Various origins/ calcite cement

Locality, Country, Description (Reference)	Depth (km)	Rm mean (%)	Th mean (°C)	Th mode (°C)	Th range low/high (°C)	Timing of Inclusions Relative to Tpeak	Present T if at Tpeak (°C)	Functional Heating Duration (yr)	Inclusion Petrography / Host Mineral
North Sea, U.K., Tartan Field									
(Th-Burley et al., 1989)									
(Rm-Bissada, 1983)									
Downthrown Block	3.7	0.7	N/A	105	88-110	early	--	$4x10^7$ [f]	Various origins/ calcite cement
Upthrown Block	3.2	N/A	105?	118?	85-118(n=3)	early	--	$4x10^7$ [f]	as above
Great Oolite Humbley Grove, U.K. (Sellwood et al. 1989)	1.5	0.55	60?	65	53-85	early or at peak	--	$3x10^7$ [f]	Various origins/ calcite cement
Great Oolite Storrington/ Southwater wells, U.K. (McLimans and Videtich, 1989)	2.6	0.7 (VRE)	N/A	90	70-95	early or at peak	--	10^7 [f]	Primaries/ calcite cement
Lodeve Basin, France. Outcrop (Landais and Connan, 1986)	0	0.85	N/A	135?	80-150	at peak	--	--	Various origins/ calcite cement
Guadalupe Mountains, outcrop, USA (Th-Crysdale, 1987) (Rm-this paper)	0	0.5 0.4? [k]	72	77	48-100	at peak?	--	10^6 [f]	Primaries/ calcite cement
Northwest Kansas, USA, wells.									
(Th-Anderson, 1989)									
(Rm-this paper)									
<u>Well names:</u>									
Cities 1 Knudsen	1.29	0.9	148	160 [d]	90-210	early	--	10^6? [f]	Primaries/ calcite cement
Gore 1 Denny	1.24	0.7	87	93 [d]	50-100	early	--	10^6? [f]	as above
Murfin 2 Elvin	1.12	0.9	59	73 [d]	45-85	early	--	10^6? [f]	as above
Sacramento Mountains, USA, outcrop.									
(data this paper)									
<u>Sample numbers:</u>									
225a-b	0	0.4 [k]	101	95	43-150	early	--	10^6? [f]	Primaries/ calcite cement
281a and 281b	0	1.2 [k]	97	100	74-108	early	--	10^6? [f]	as above
282-a	0	0.4 [k]	93	120	60->200	early	--	10^6? [f]	as above
283-a	0	0.4 [k]	74	75	47-160	early	--	10^6? [f]	as above

Notes

Abbreviations: Rm, mean random vitrinite reflectance; VRE, Vitrinite reflectance equivalent estimated form regional curves or other measured thermal maturity parameters; Th, homogenization temperature, mean or mode value as indicated; n=sample size, noted only if small. Tpeak is the peak temperature reached in a system. Tp, is the present temperature in the system. Functional heating duration is the time elapsed while temperature increases within 15°C of peak temperature. N/A means not available. -- indicates not applicable. An underlined mean Th value indicates that the modal Th value was not available and the mean value was used in figure 2 and to compute the regression equation. A question mark infers some uncertainty in the determination or measurement.

Compilation Notes: a, The term, primaries, refers to fluid inclusions petrographically recognized to have formed during crystal growth; b, fluid inclusions appear to have formed near peak temperature; c, heating is related to an igneous intrusion, which usually cool in less than 1 m.y.; d, used highest substantial mode (numerous measurements) in polymodal Th distributions; e, fluid inclusions appear to have formed before peak temperature; f, heating duration estimated from residence time within 15°C of peak temperature; g, heating duration estimate from Barker (1983); h, corrected using American Association of Petroleum Geologists (1976) method; i, reconstructed from geothermal gradient and mean surface temperature; j, well temperature after equilibration in the well was allowed; k, weathered sample; l, reported temperature (corrected); m, considered data only from the primary fluid inclusions; n, average or interpolation from adjacent samples; o, Rm from nearby well that has a similar temperature-depth profile and mineral assemblage changes with depth; p, Rm estimated from an H/C ratio of 0.9 in associated organic matter; q, pressure correction removed from data reported as Th.

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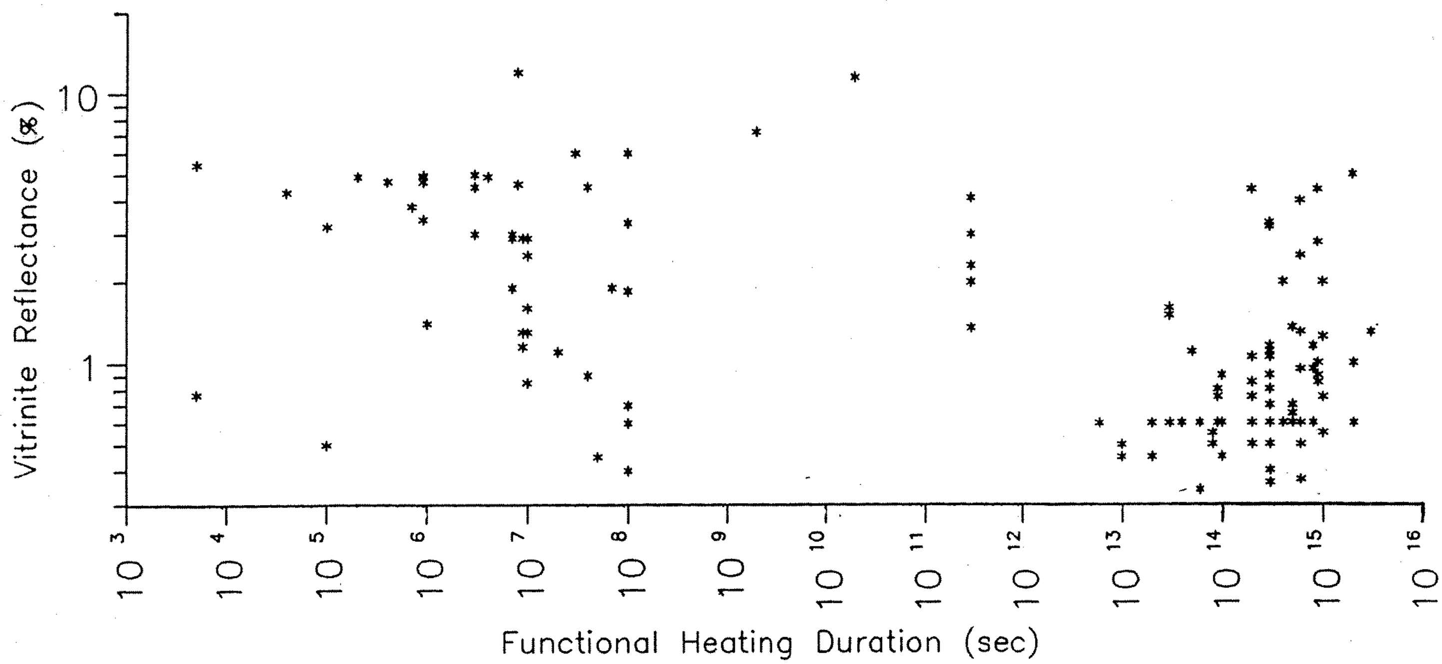
Figure Captions for Supplementary Materials

Figure 1. Scatter Plot of functional heating duration versus vitrinite reflectance for contact metamorphism adjacent to igneous sheet intrusions, geothermal systems, and burial diagenesis. Plot uses data from this paper and Barker (1989a; tables 5.2,5.3,5.4). Time units given in seconds because this unit is used in kinetic equations, although the functional heating duration is measured in millions of years (m.y.) (conversion factor: 3.15×10^{13} sec = 1 m.y.).



Barker-Goldstein Supplementary Fig.