Machine Learning Mineralogy Classification Comparison to Empirical Log Relationship and Implication for Physics Informed Modeling

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CREWES meeting Dec 2, 2022

Objective

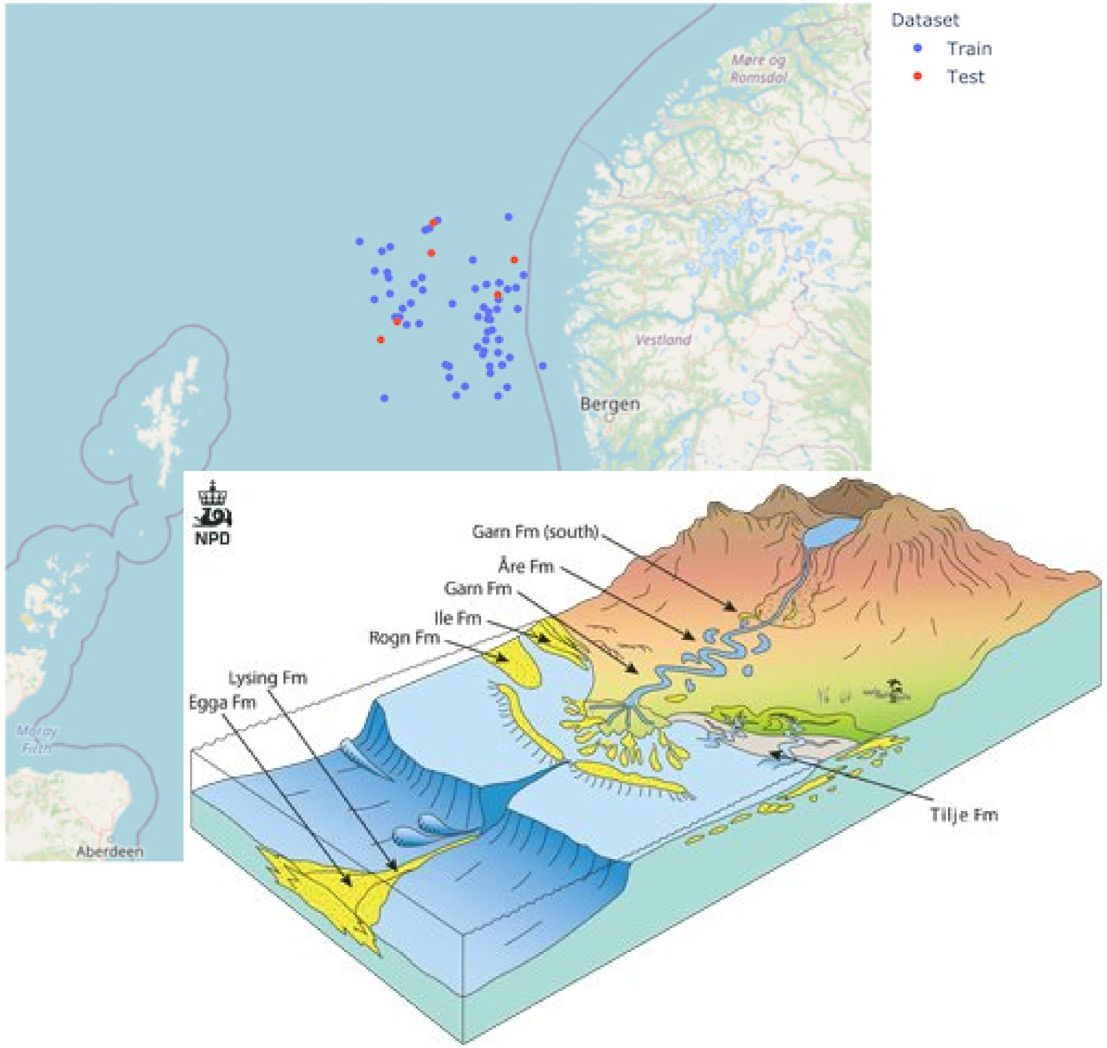
The objective was to predict lithology labels from well logs and provided lithostratigraphy.

Data

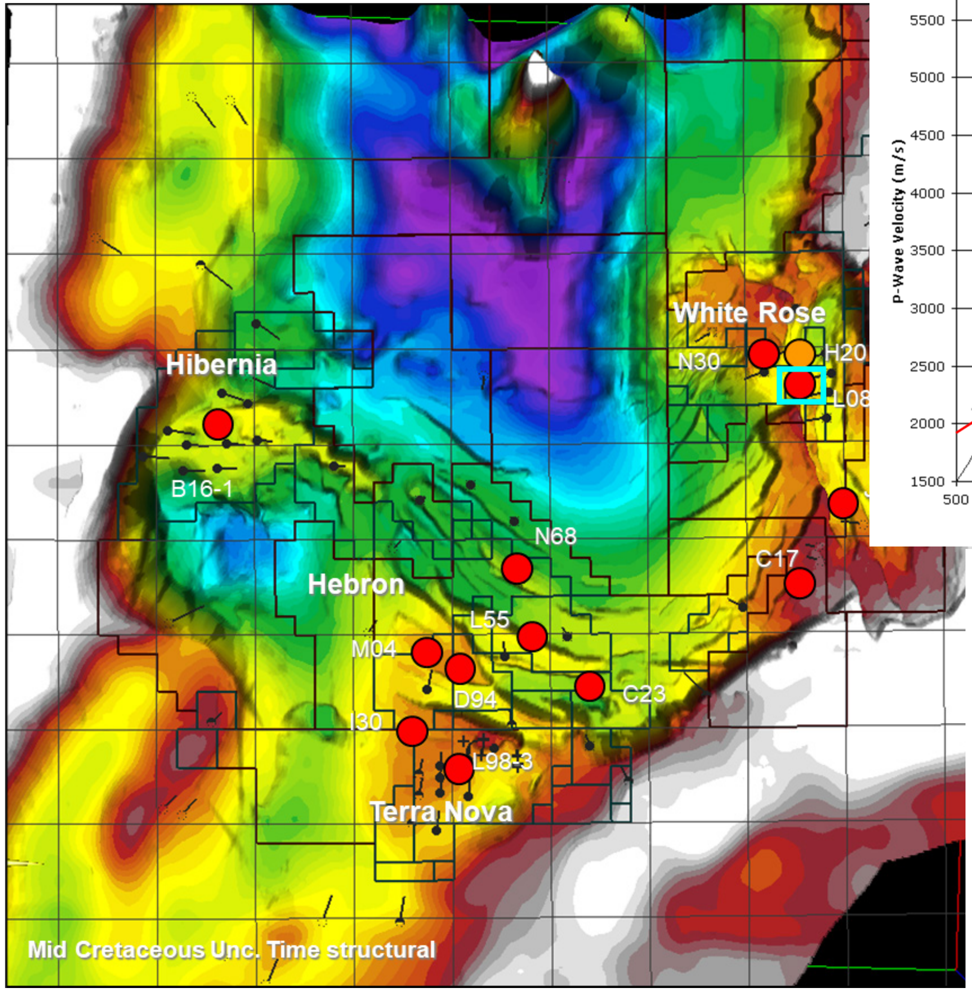
The dataset spans 118 training wells in the South and North Viking graben offshore Norway.

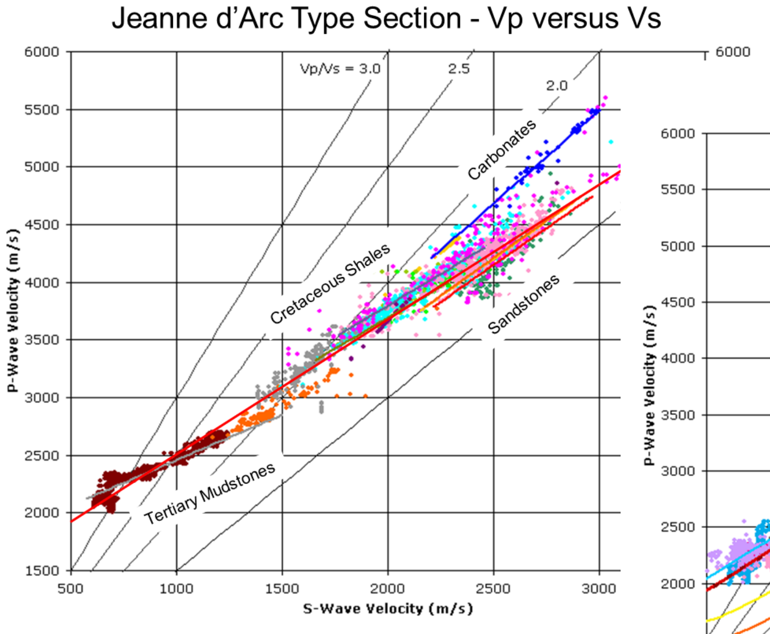
Advantage

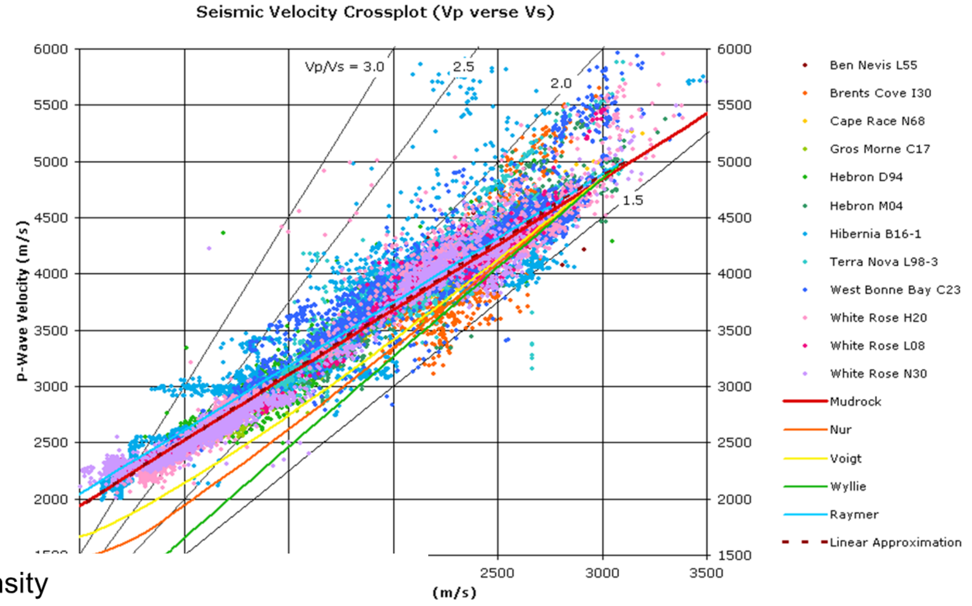
118 wells with petrophysical analysis
1.5 million samples, 300,000 points with complete data.

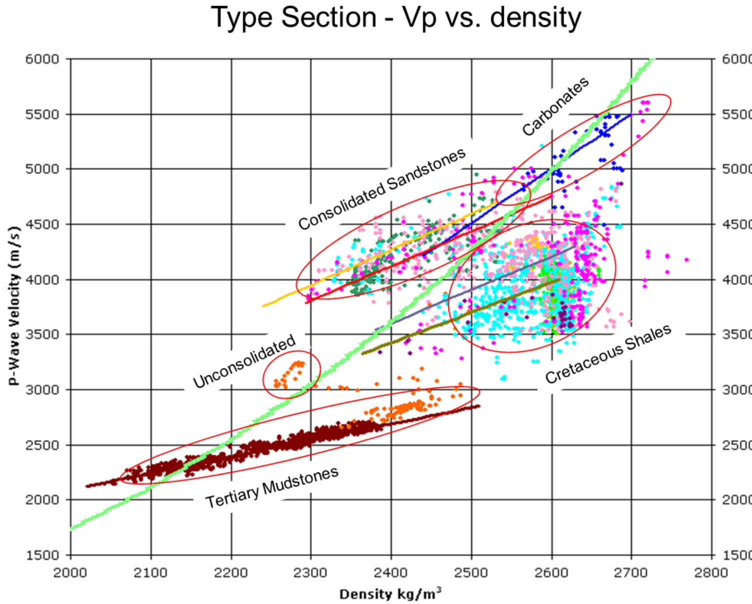


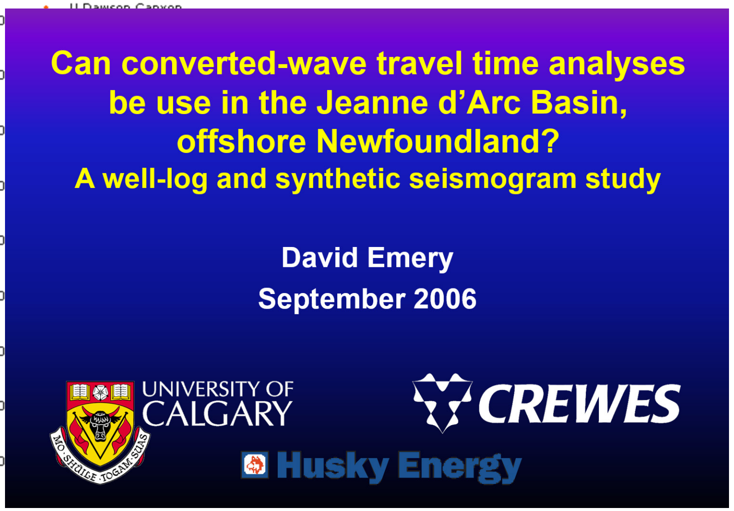
2006 Master Project – Vp, Vs & ρ relationship to lithology



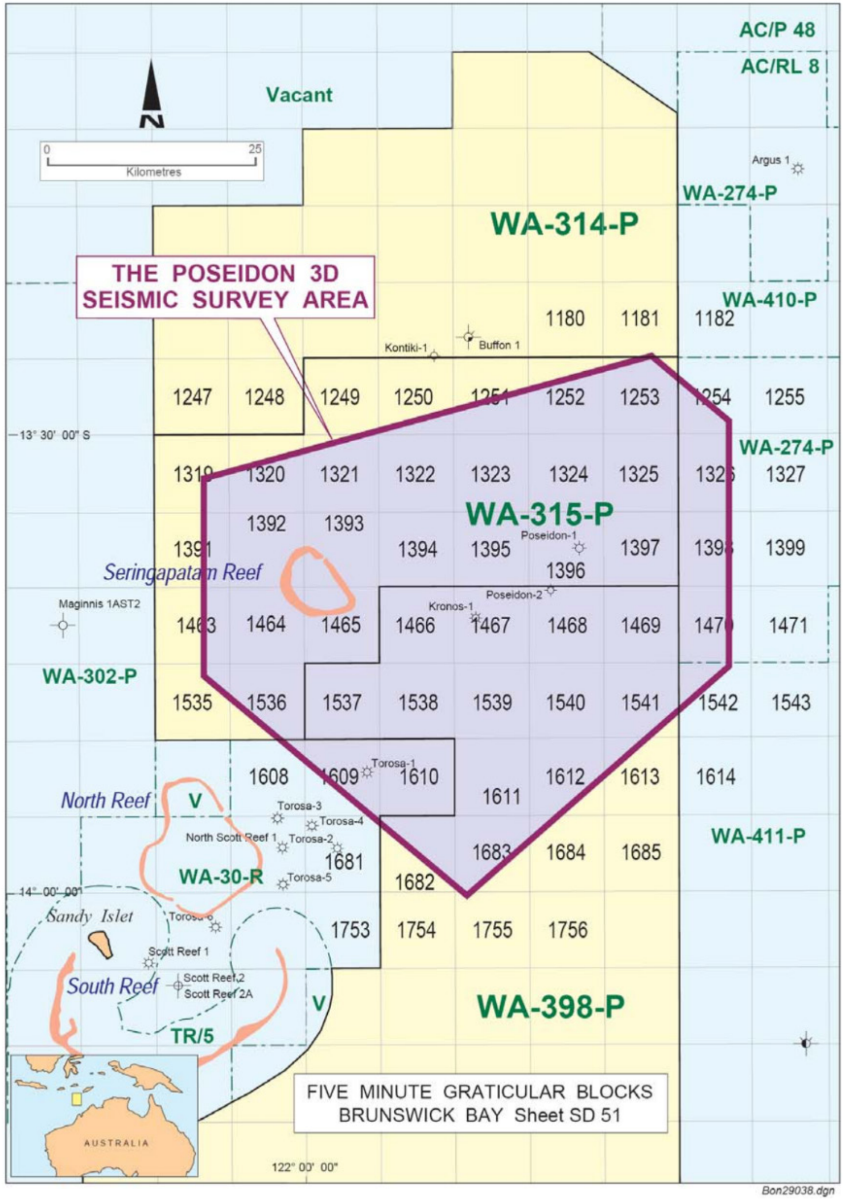








Poseidon 3D NW Shell Australia



Made available by Geoscience Australia, and ConocoPhilips.

Data

Acquired in 2009, 9 wells, migrated stack and 3 offset gathers

Geophysics Society of Houston (GSH) Geophysics in the Cloud competition 2021

Geoscience Australia

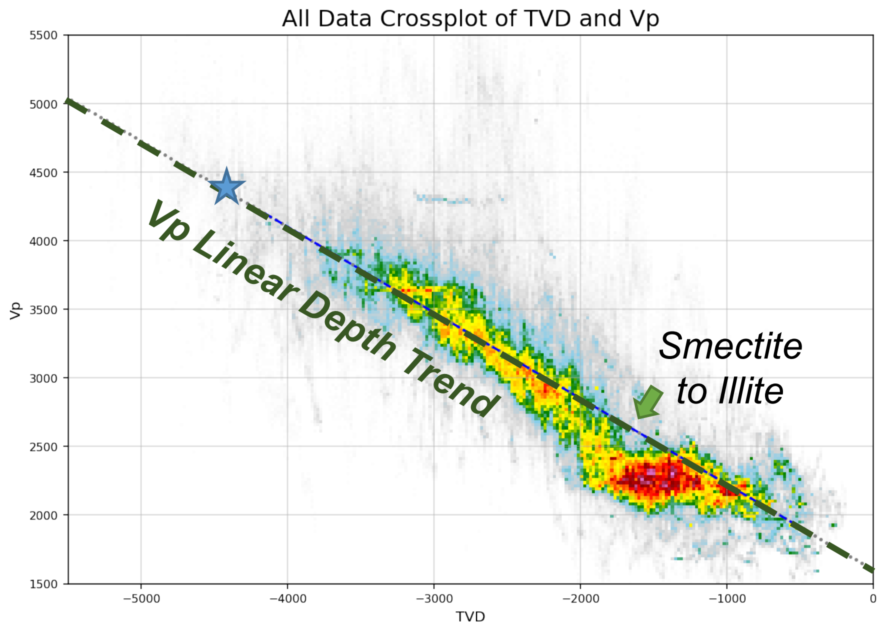
Luping Qu

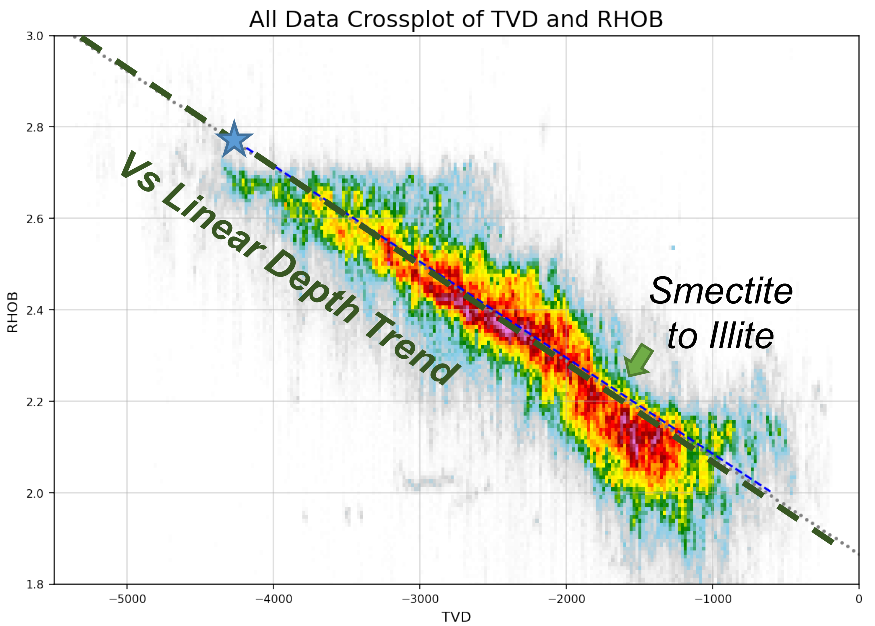
Ph.D. Candidate at University of Calgary and member of CREWES

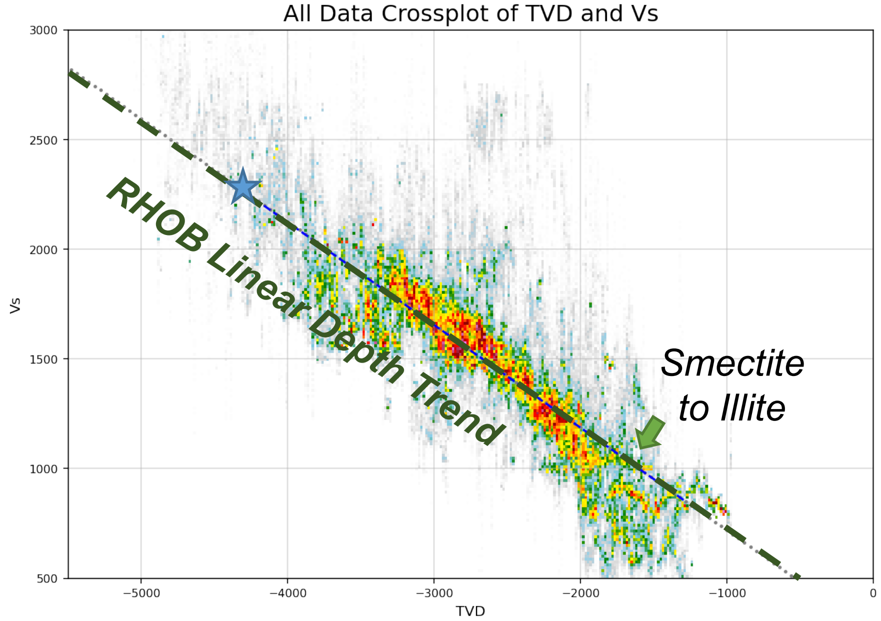
Kai Zhuang

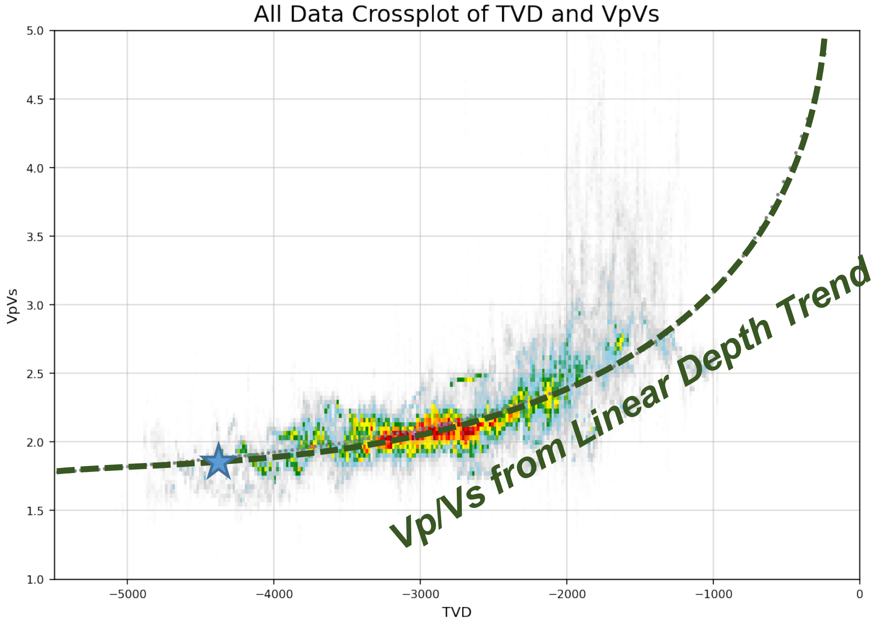
Ph.D. Candidate at University of Calgary and member of CREWES

Attribute Depth Trend

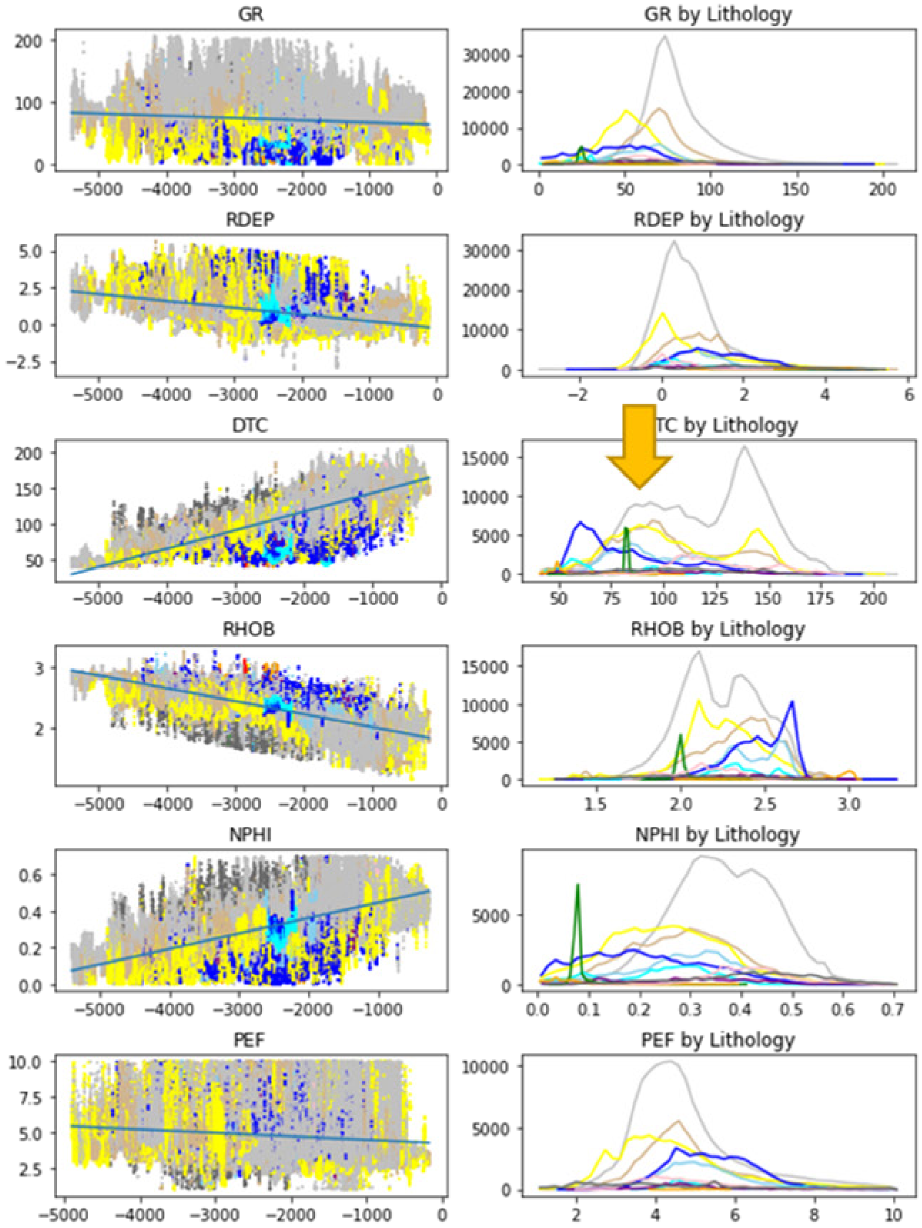


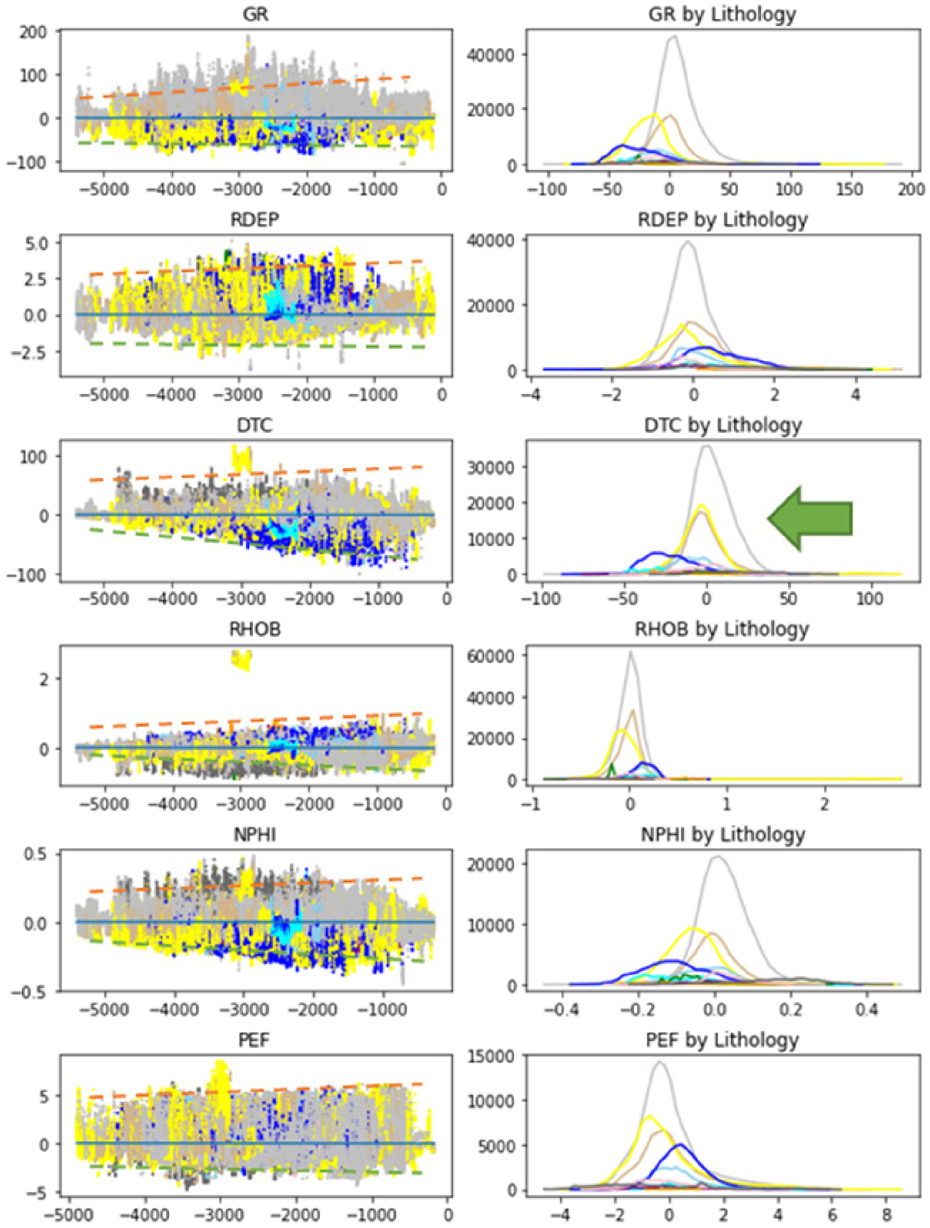




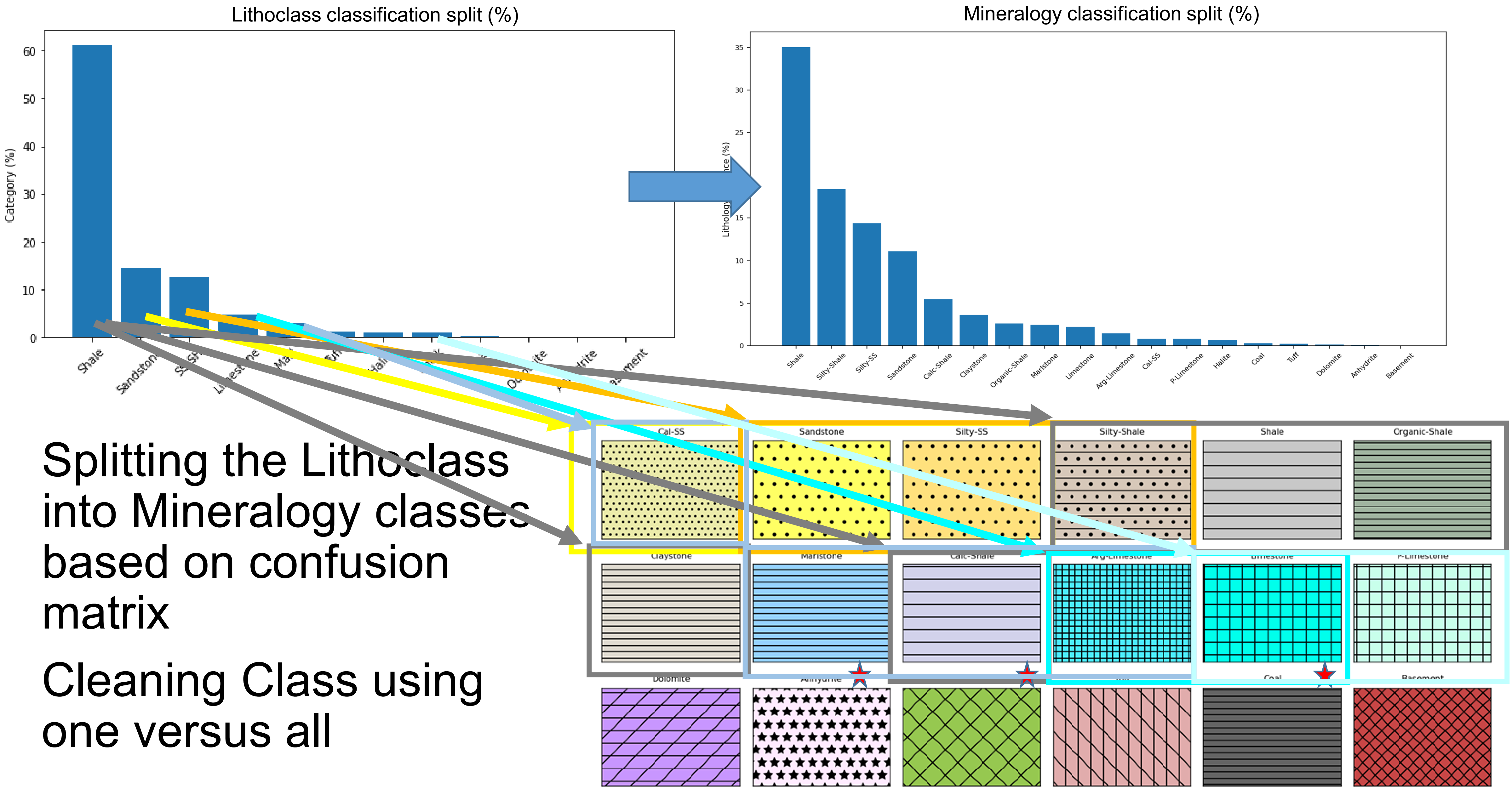


Feature Engineering





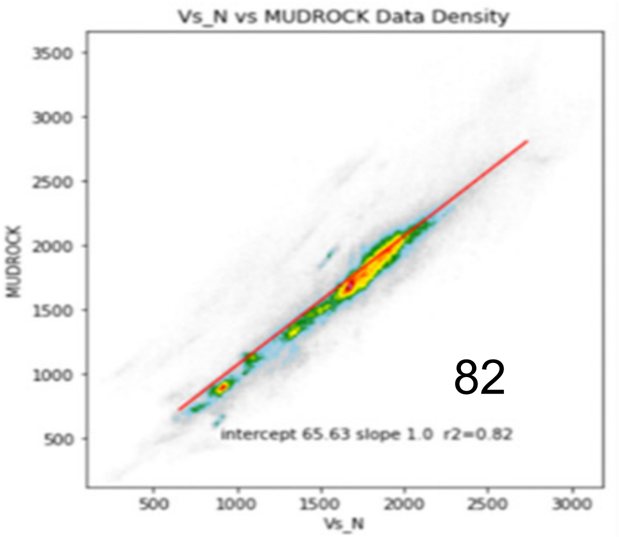
Lithoclass to Mineralogy Classes

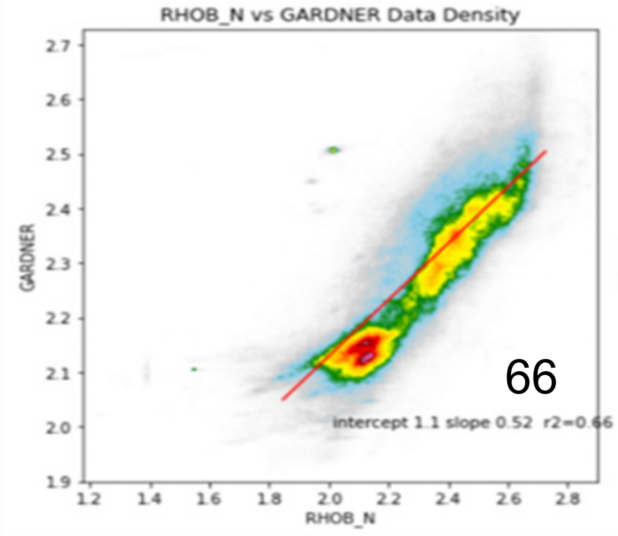


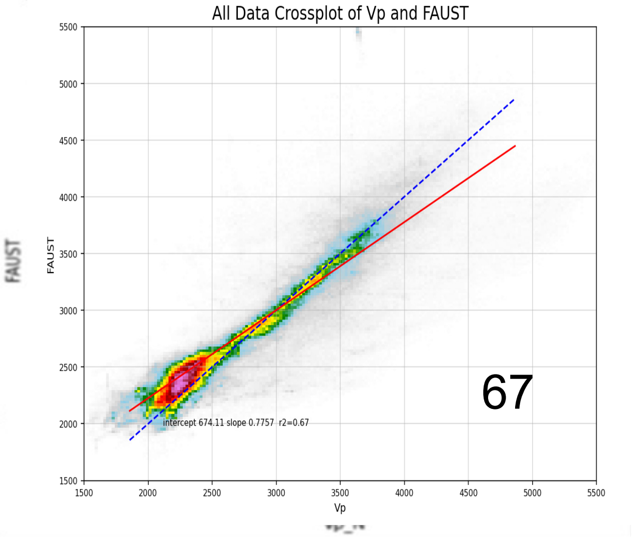
Splitting the Lithoclass into Mineralogy classes based on confusion matrix

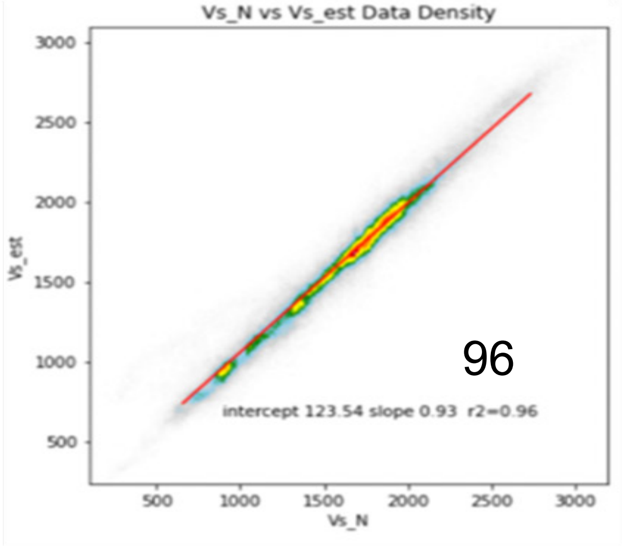
Cleaning Class using one versus all

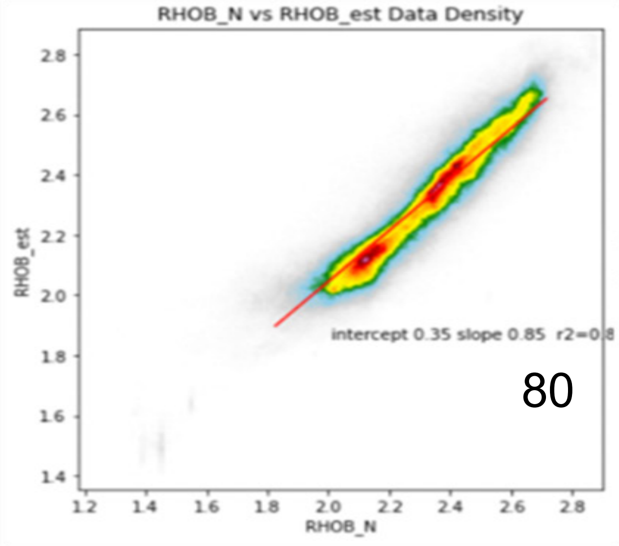
Empirical Relationship

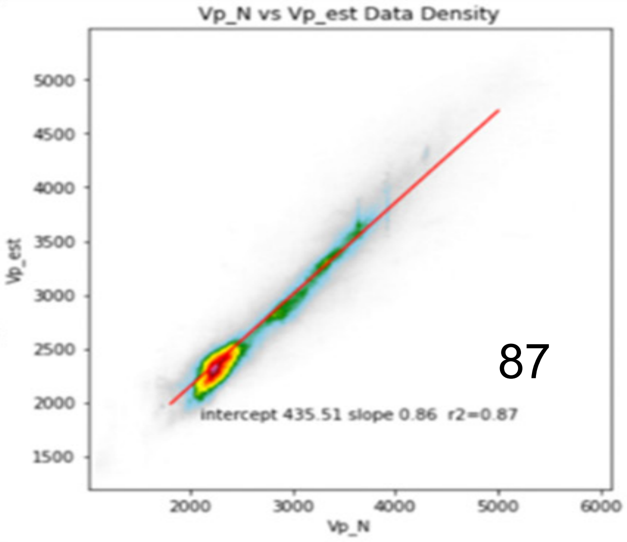






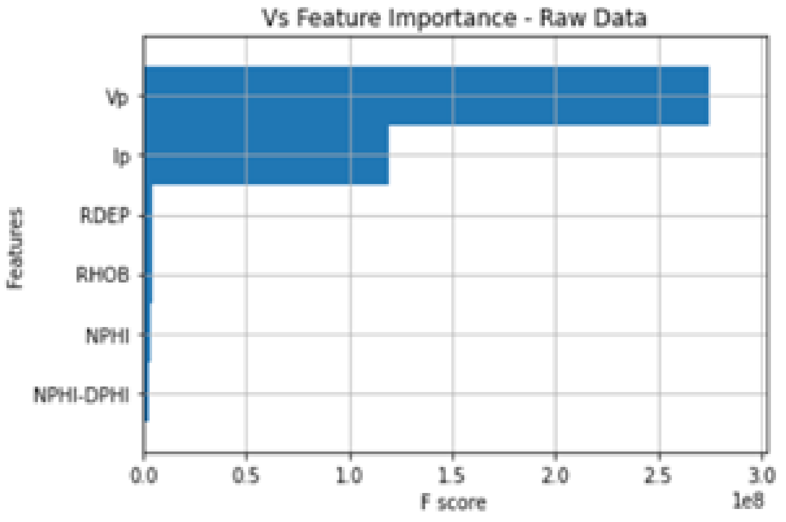


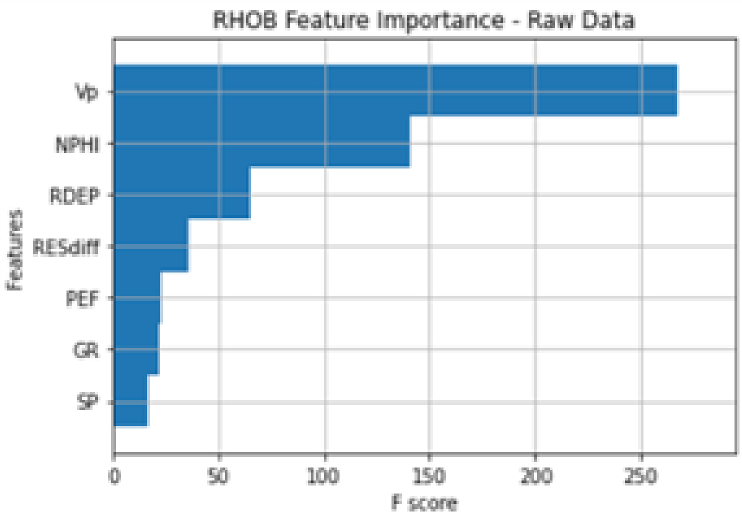


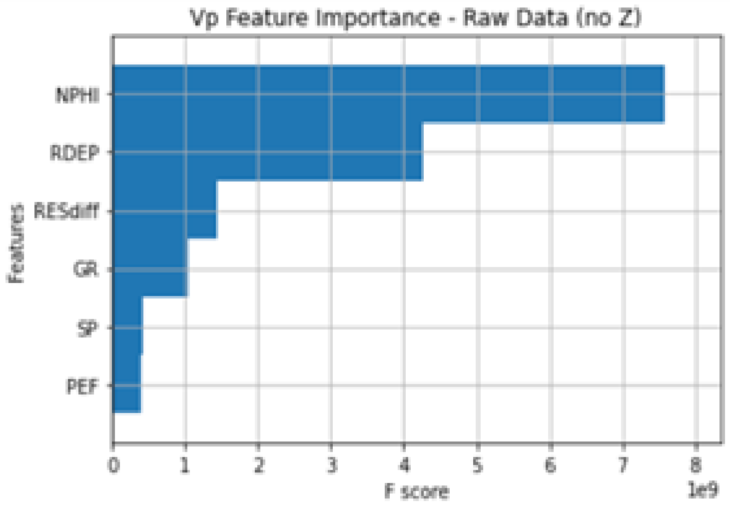


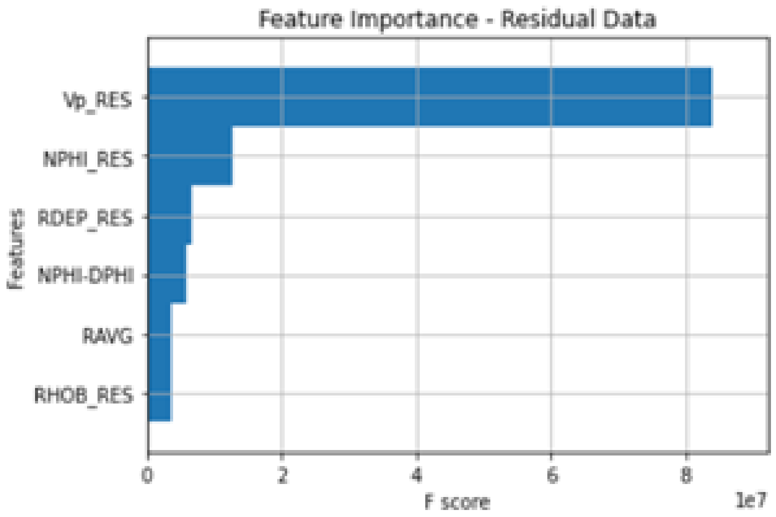
Machine Learning Results

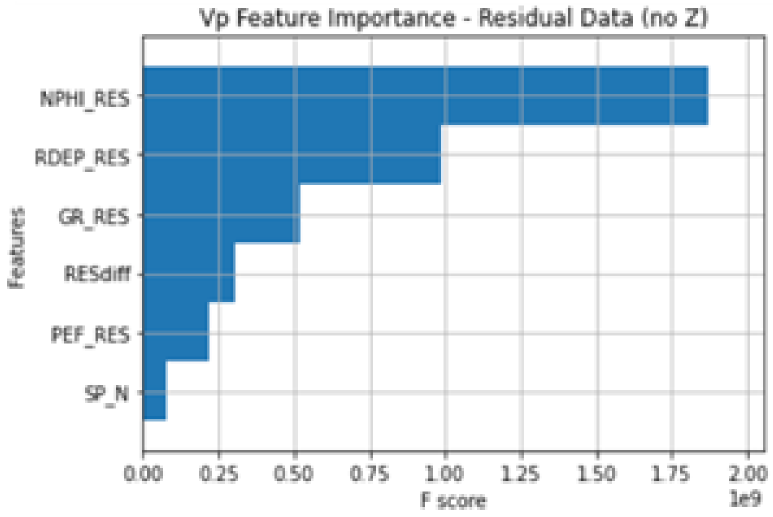
Feature Importance



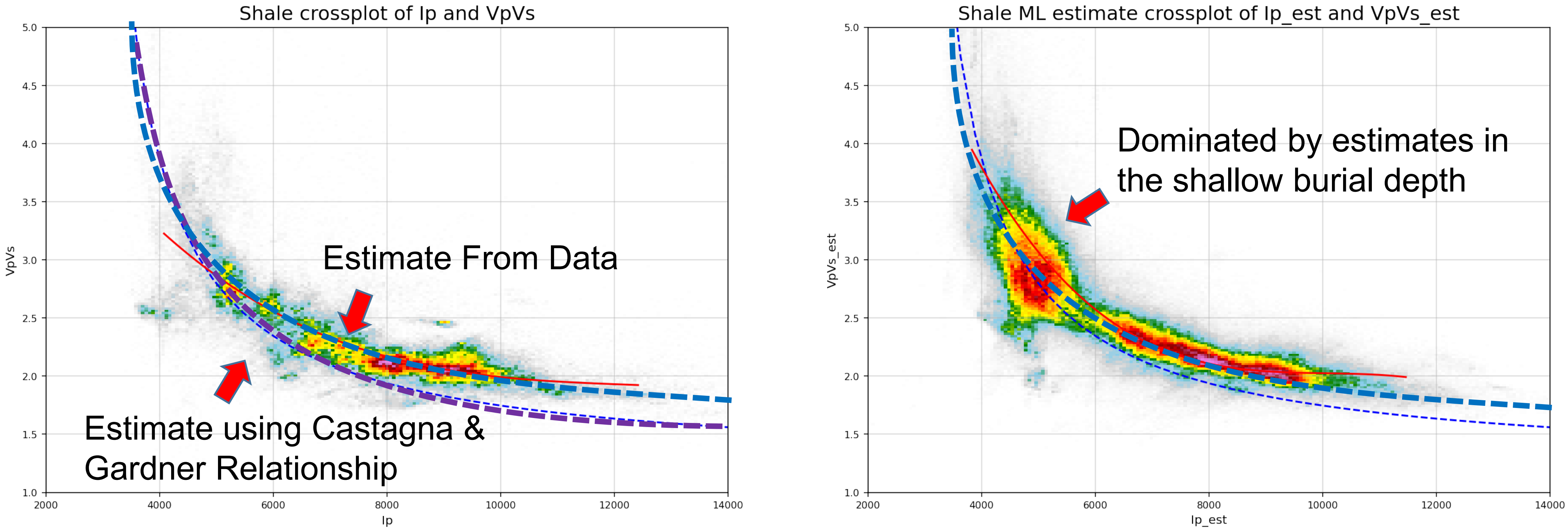






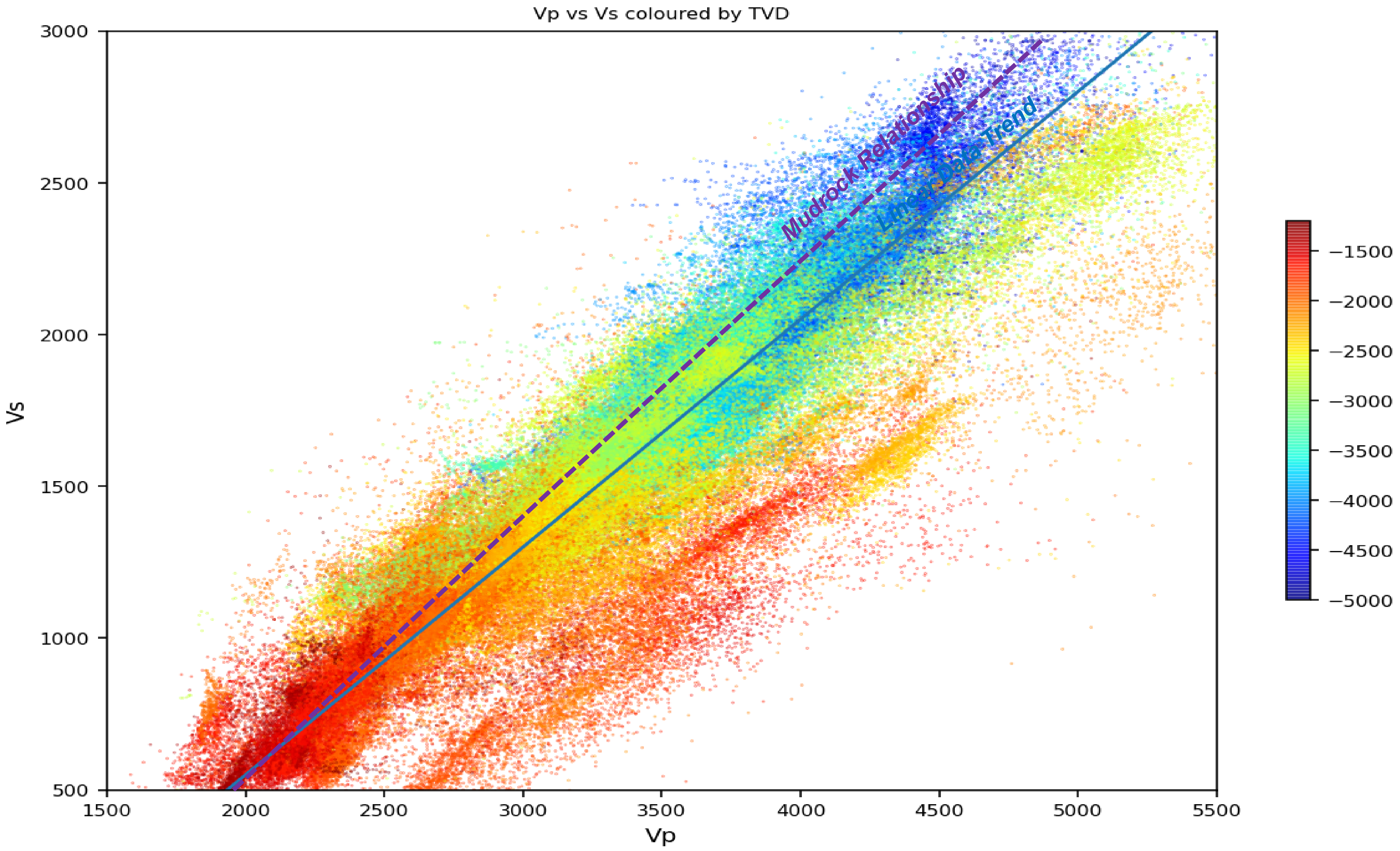


Machine Learning Results using provide labelled data

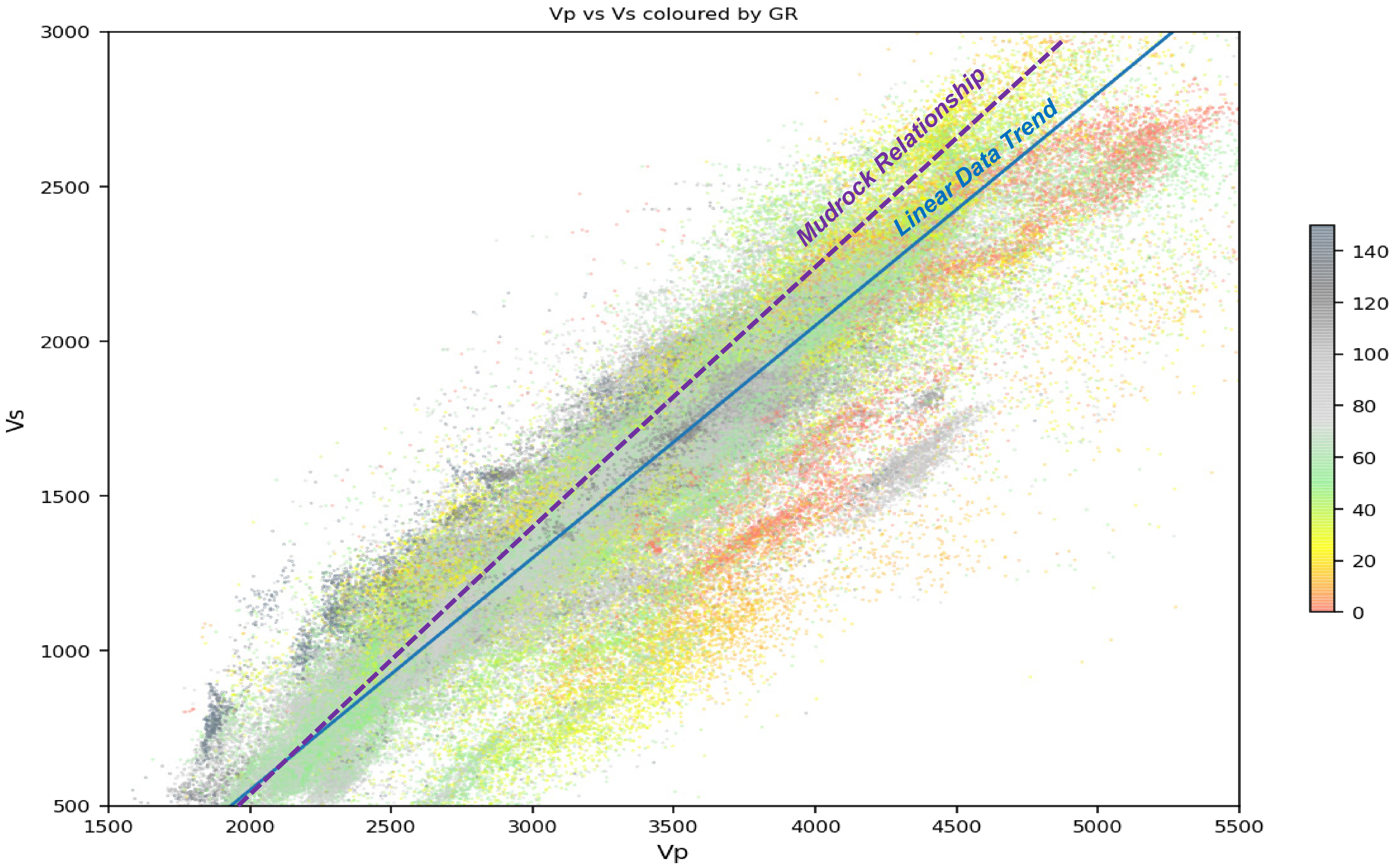


Solution follow the trend for empirical relationship but not the absolute values. Significant part of the missing data was in the shallow part of the section.

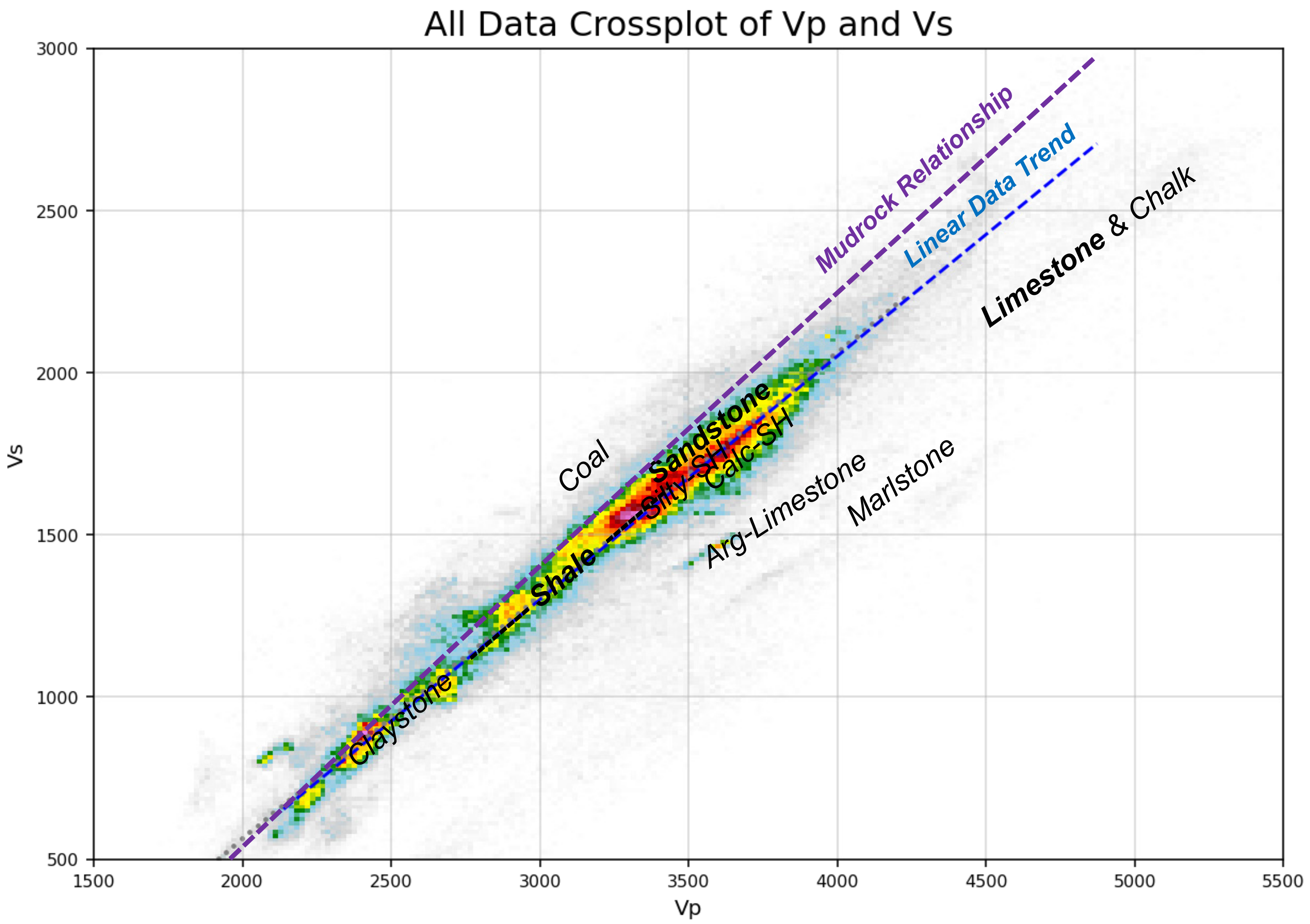
Input Data Coloured by Depth



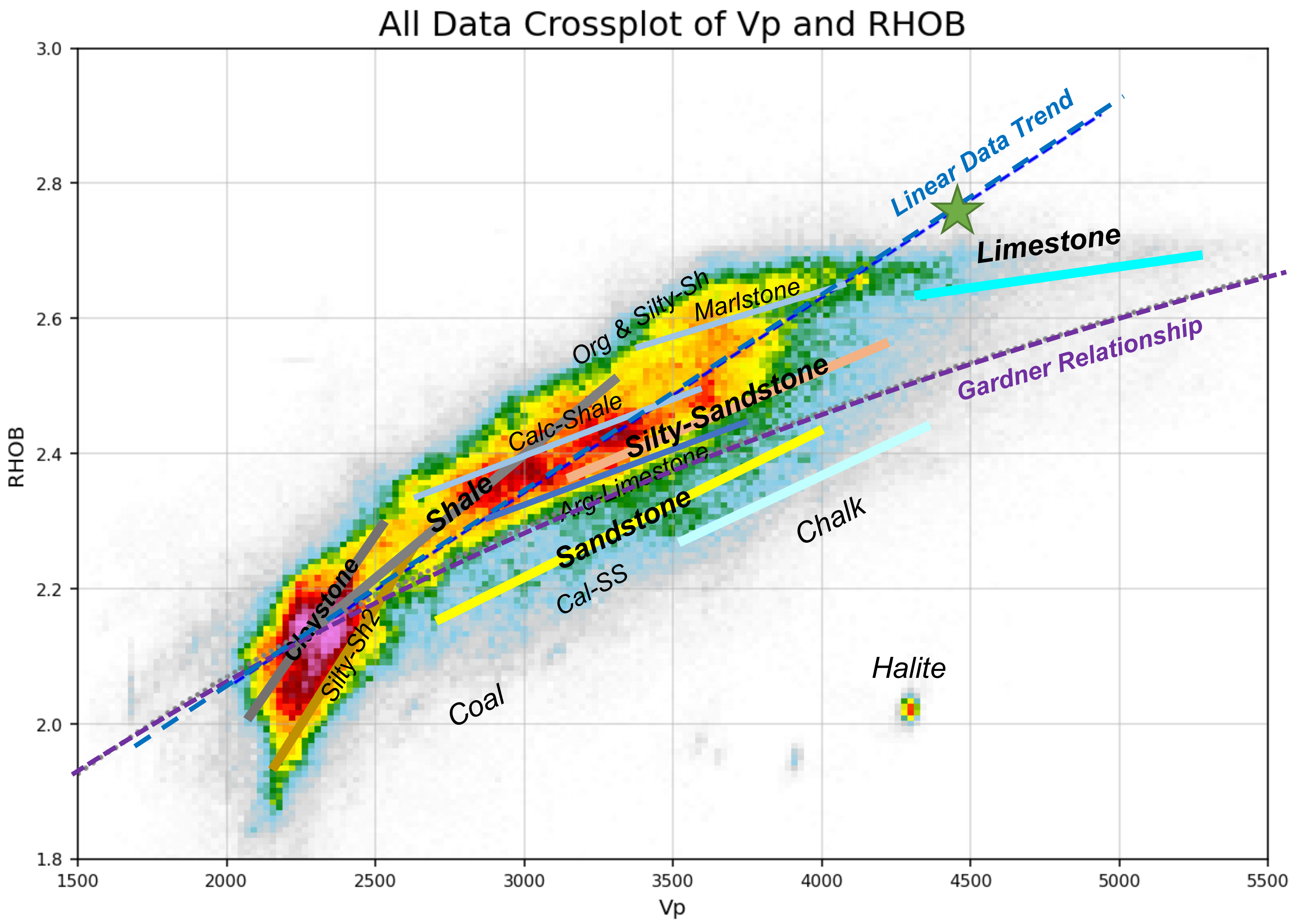
Input Data Coloured by GR



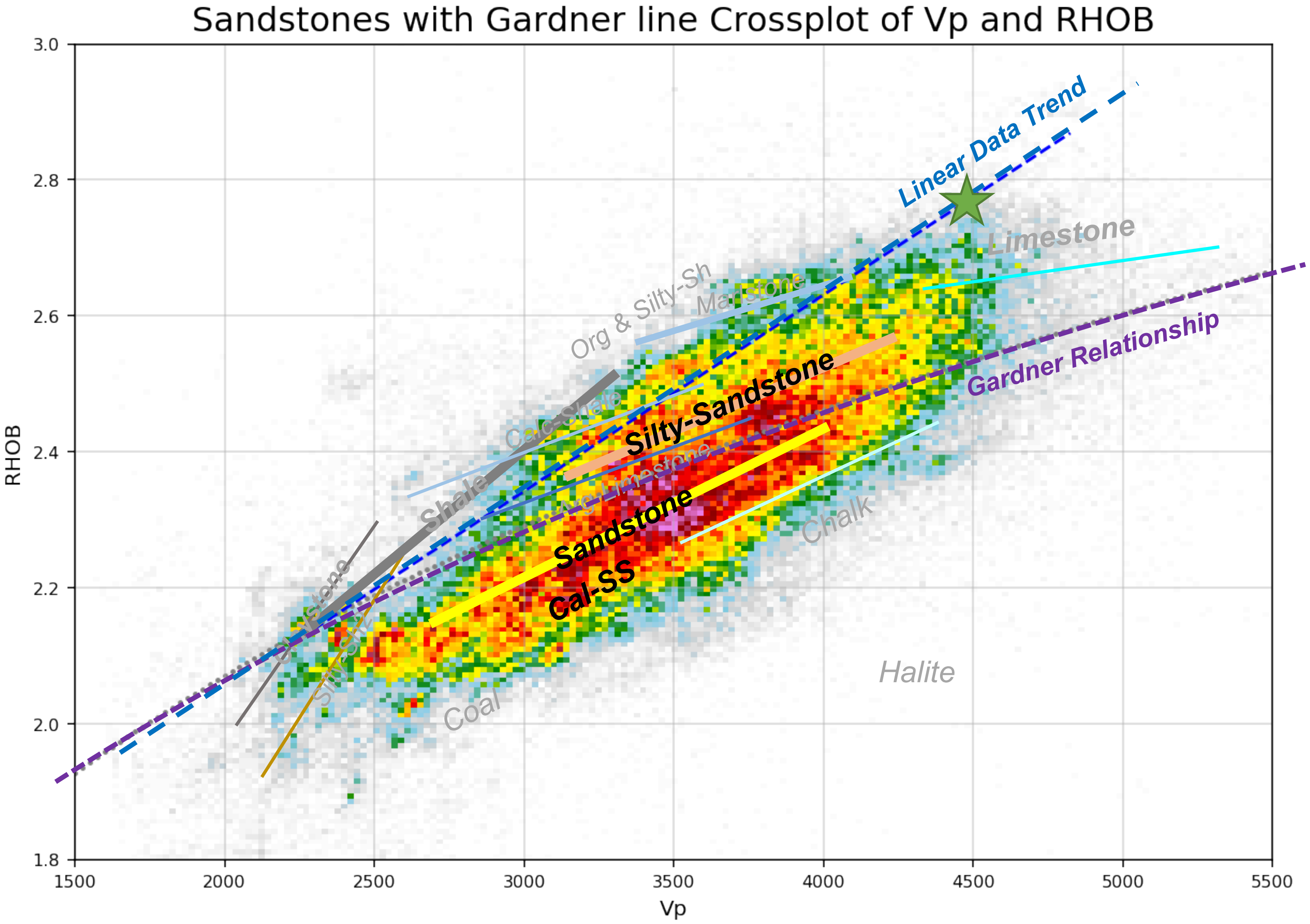
Mudrock Relationship (Colour by data density)



Gardner Relationship

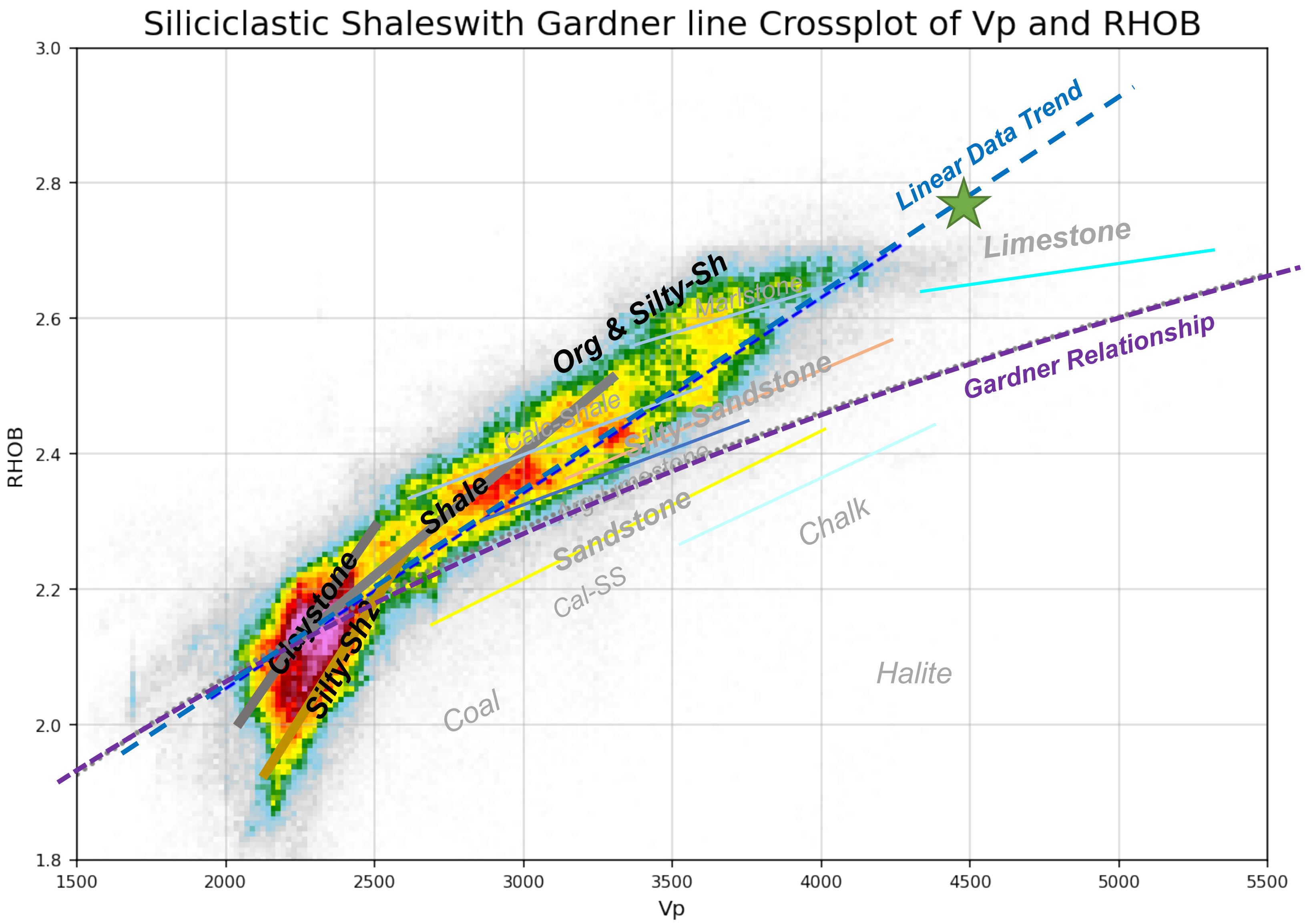


Sandstones

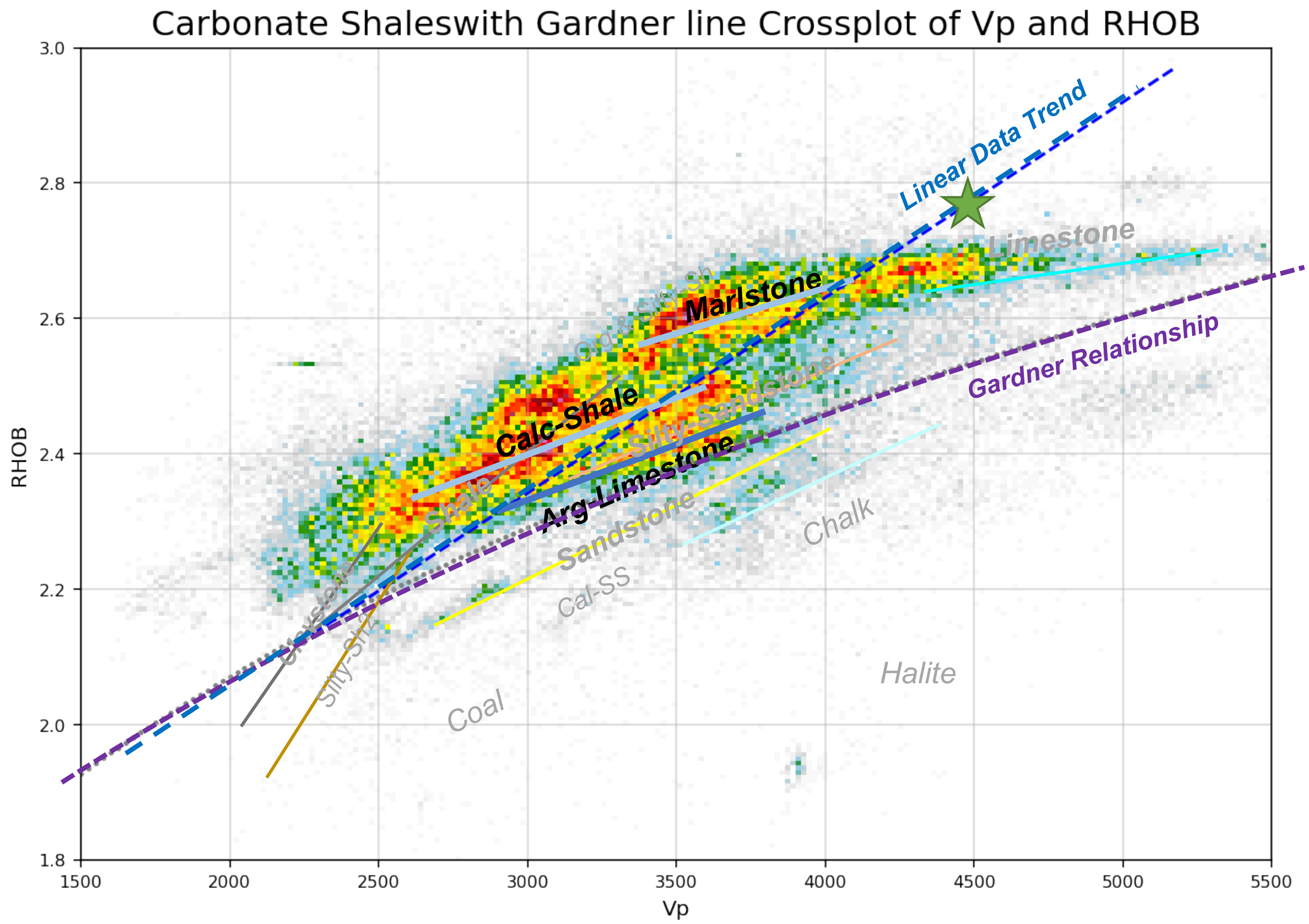


Sandstones with Gardner line Crossplot of Vp and RHOB
RHOB
Vp
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1500
2000
2500
3000
3500
4000
4500
5000
5500
Linear Data Trend
Limestone
Org & Silty-Sh
Marlstone
Gardner Relationship
Silty-Sandstone
Calc-Shale
Shale
Sandstone
Chalk
Cal-SS
Coal
Halite

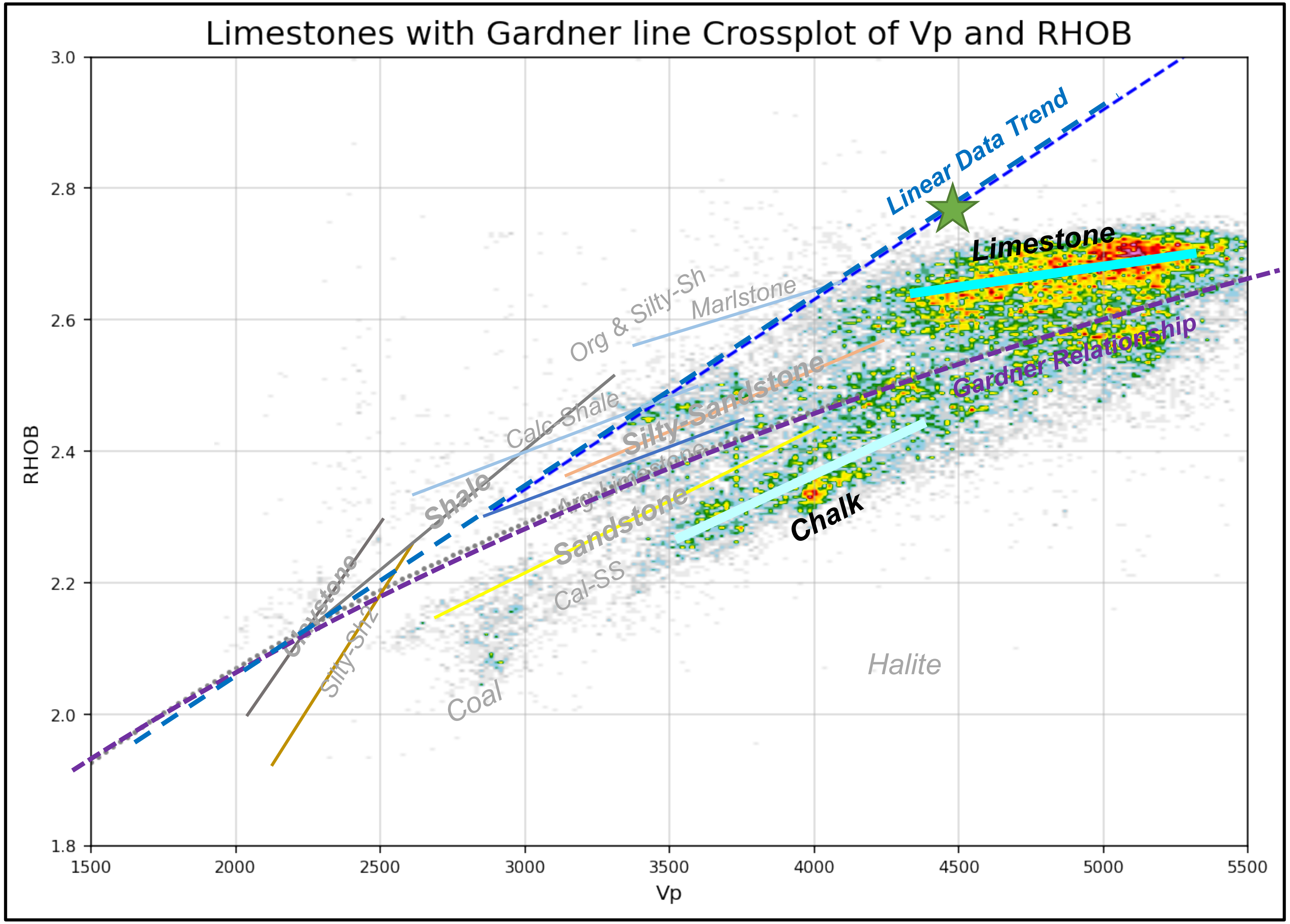
Siliciclastic Shales



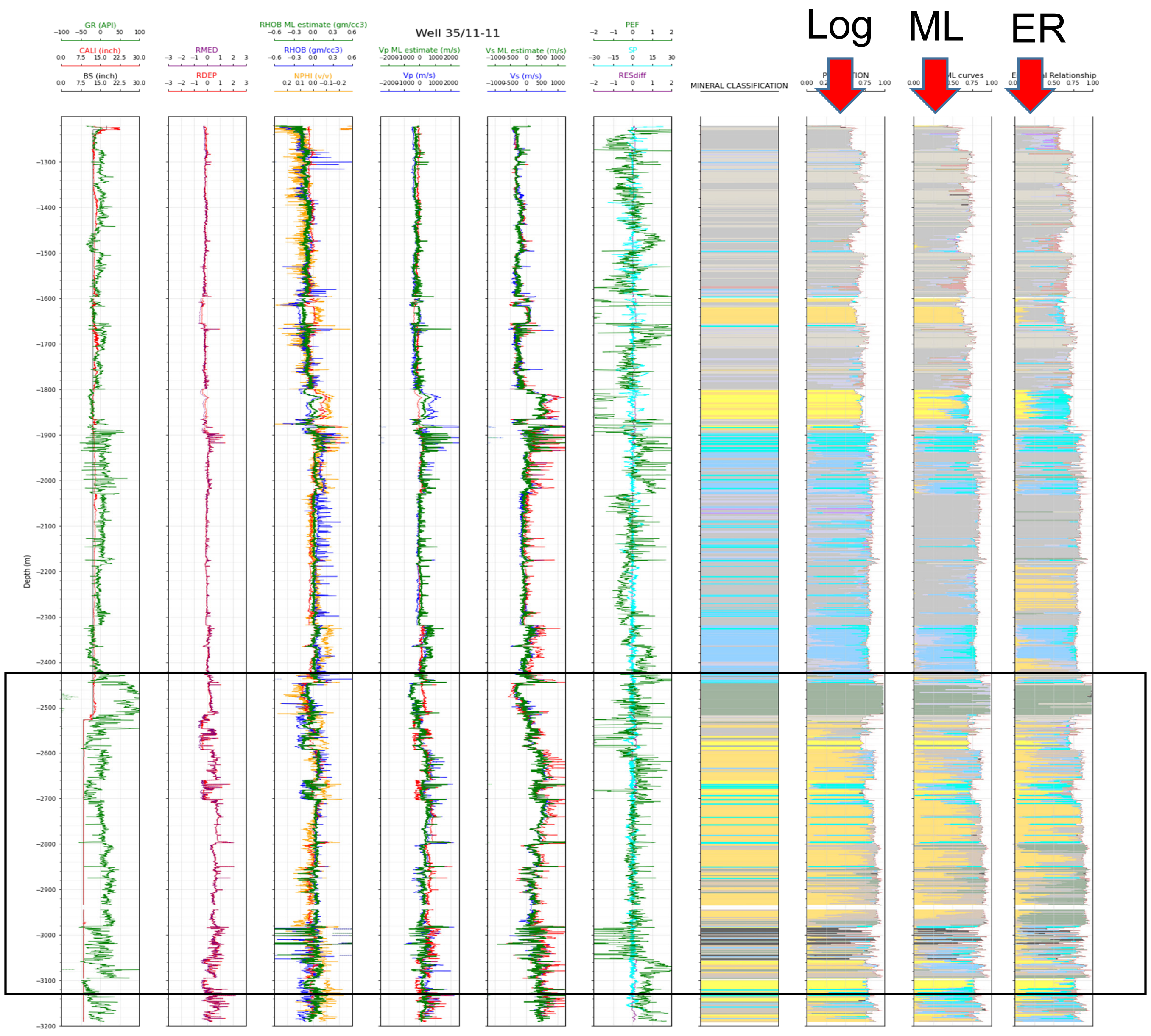
Calcareous Shales, Marlstones and Arg Limestone



Limestones & Chalks



ML mineralogy prediction using logs, ML curves, & Empirical relationships



Faust 1951 & 1953

$$V_p = \gamma (ZF)^{1/6}$$

$$where\ F = R_t / R_w$$

Gardner 1974

$$\rho = c V_p^{.25}$$

Castagna 1985

$$V_s = 0.8621 \times V_p - 1172$$

ML estimate are better than empirical relationship but still tend to favour the dominate classes.

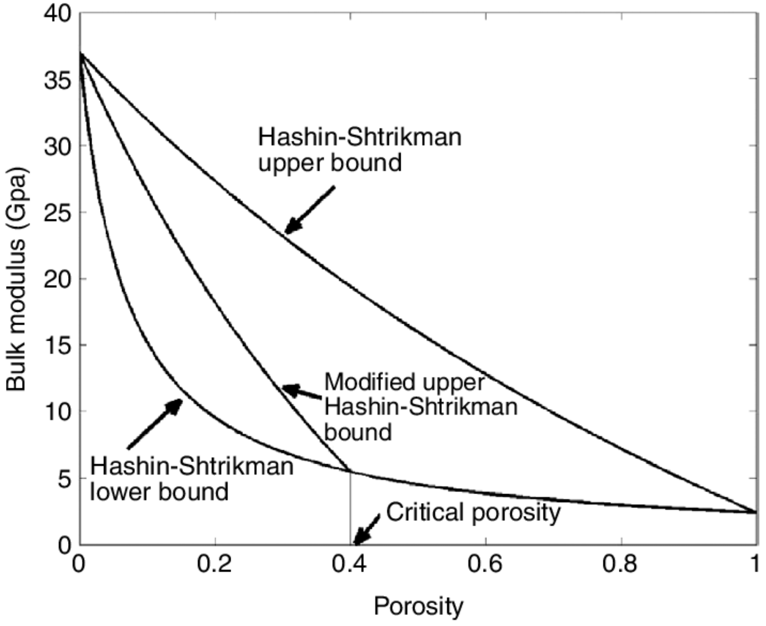
Elastic constants for isotropic media

$$E = \frac{\rho V_s^2\left(3V_p^2 - 4V_s^2\right)}{V_p^2 - V_s^2} \qquad \sigma = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - 2V_s^2\right)}$$

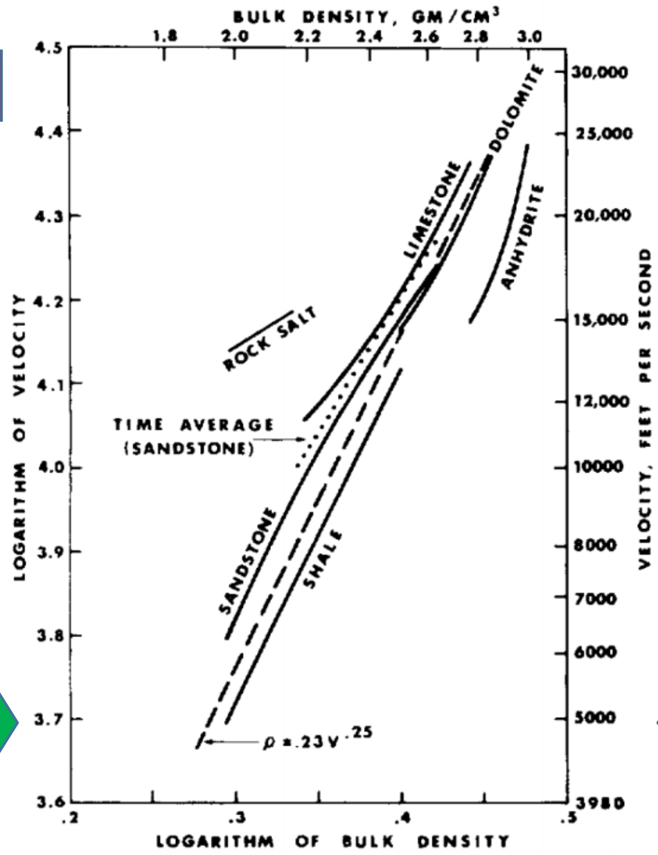
$$K = \rho\left(V_p^2 - {}^4\!/_3\, V_s^2\right) \qquad \mu = \rho V_s^2$$

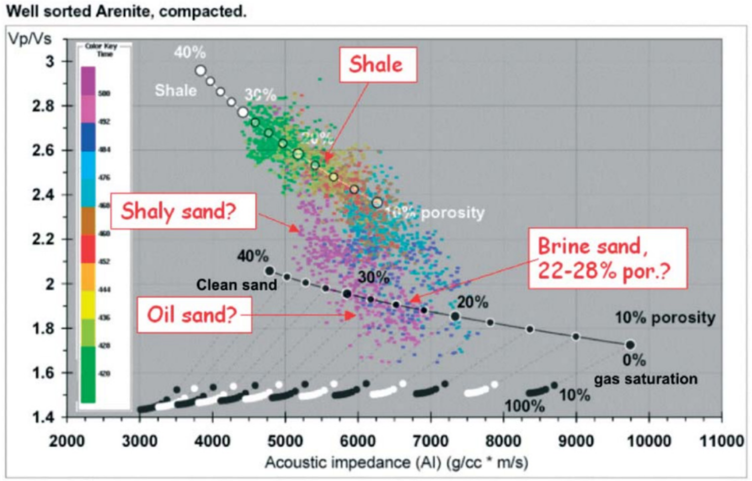
$$\lambda = \rho\left(V_P^2 - 2V_S^2\right) \qquad I_p = \rho V_p$$

$$\mu = \rho V_s^2 \qquad I_S = \rho V_s$$



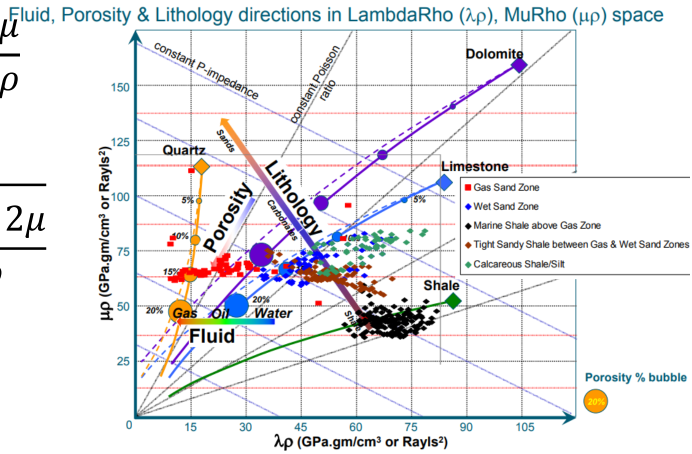
$$Vp = \sqrt{\frac{k + {}^4\!/_3\,\mu}{\rho}} \qquad Vs = \sqrt{\frac{\mu}{\rho}}$$





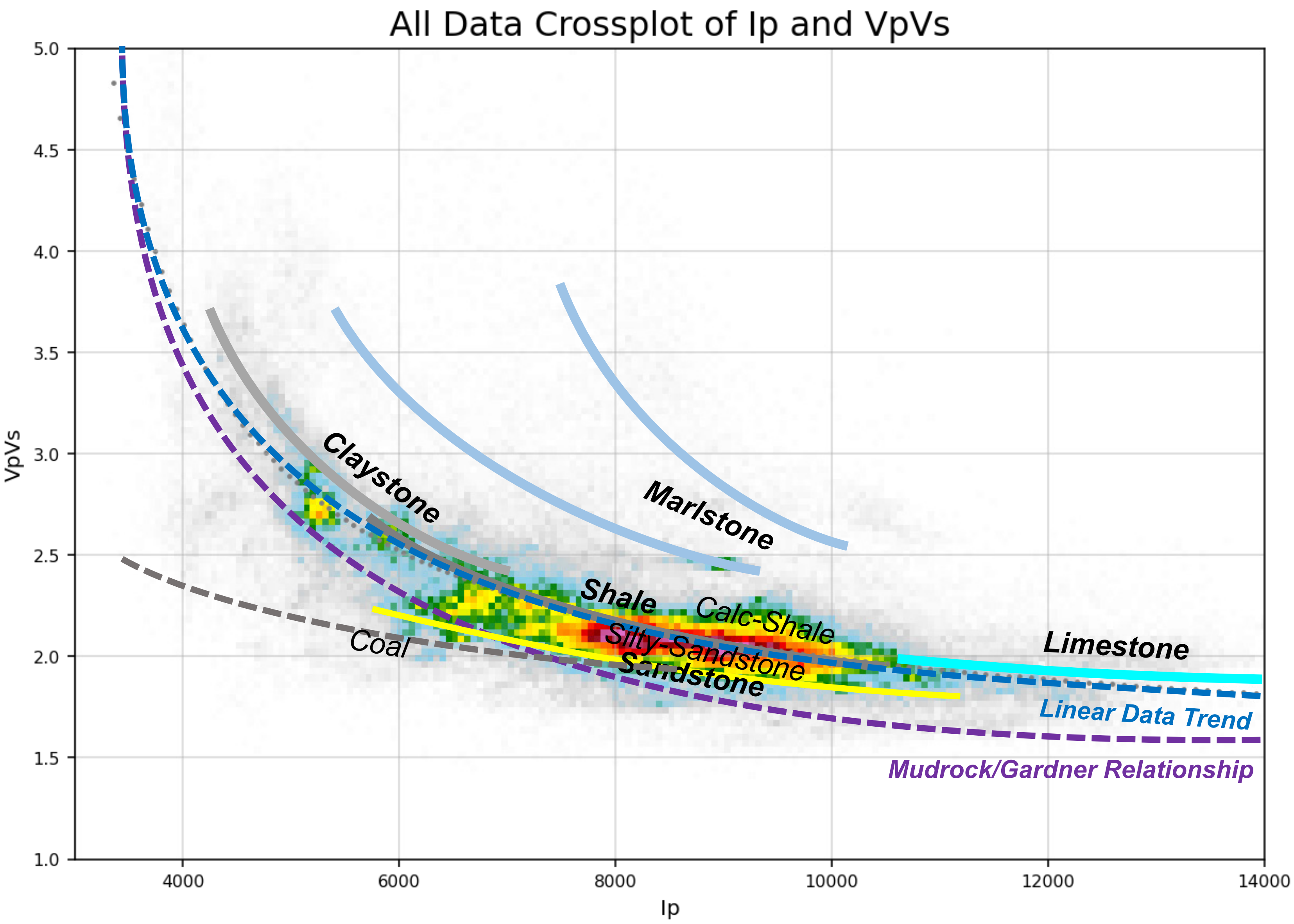
$$Vs = \sqrt{\frac{\mu}{\rho}}$$

$$Vp = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

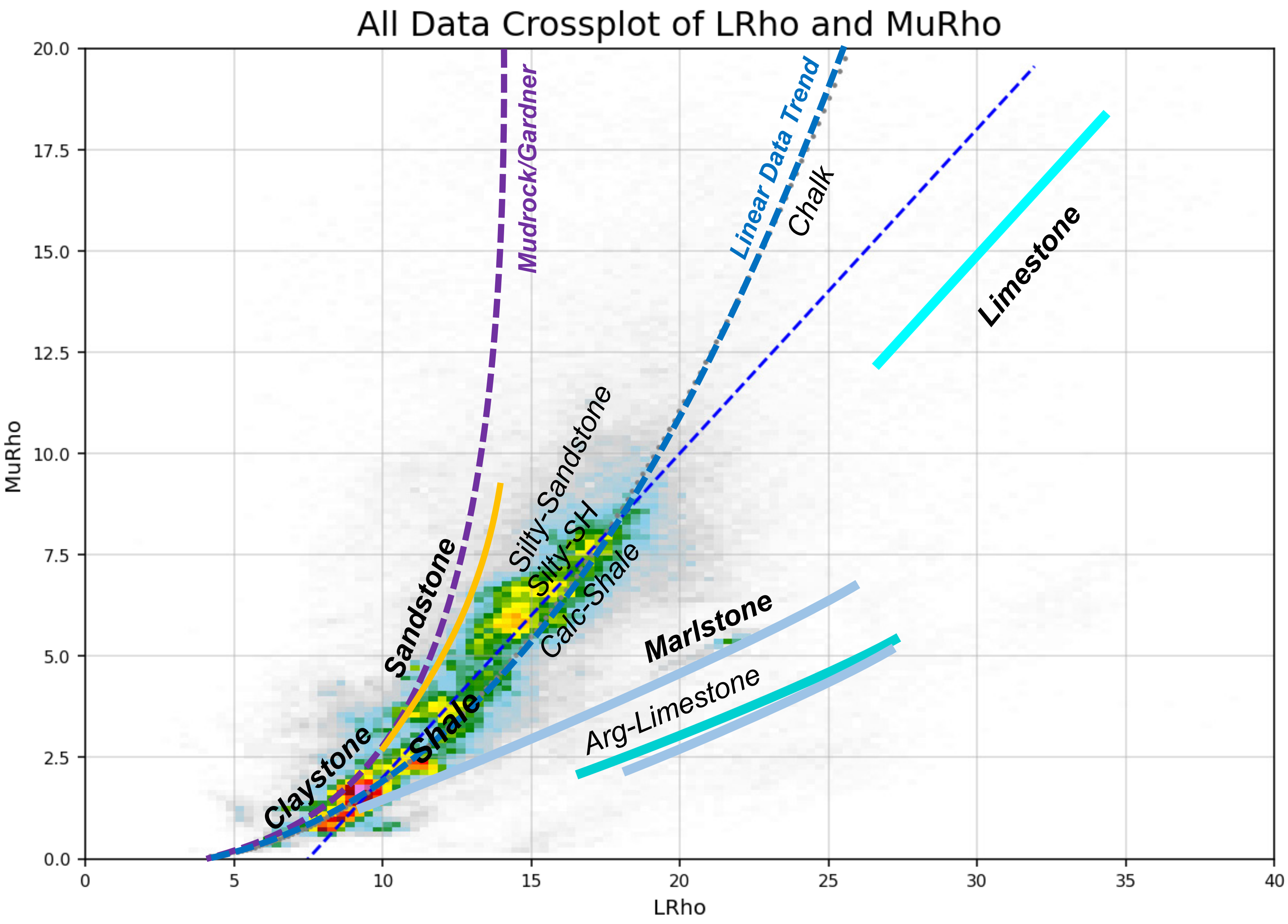


(Adapted from Hoffe, Perez and Goodway CSEG convention 2008)

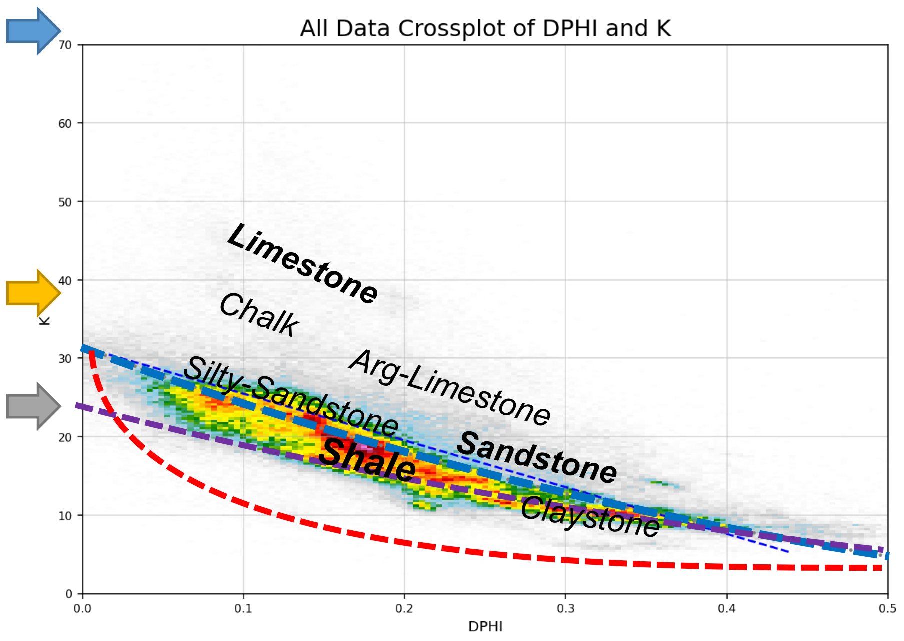
Vp/Vs versus Ip

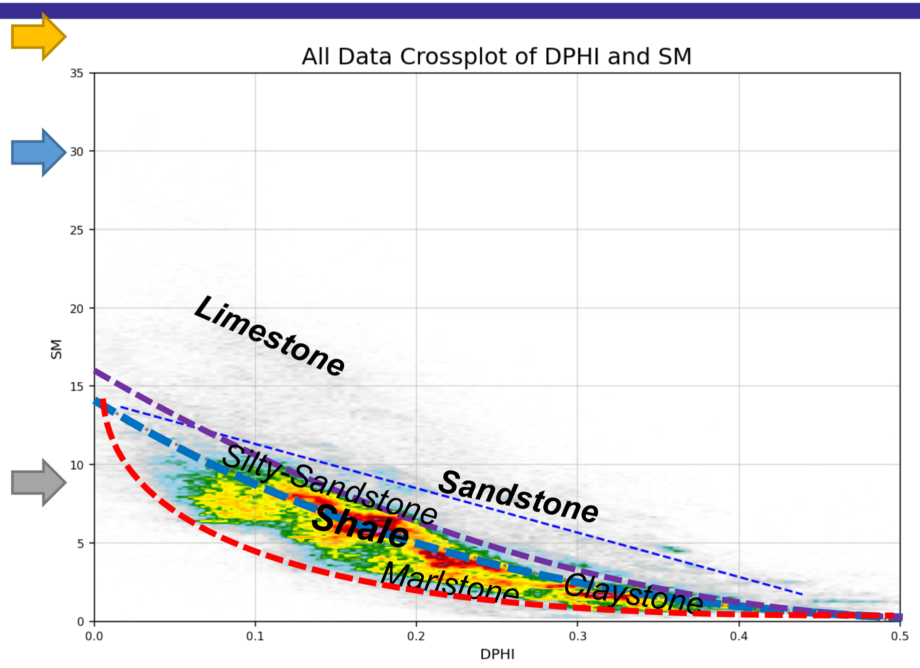


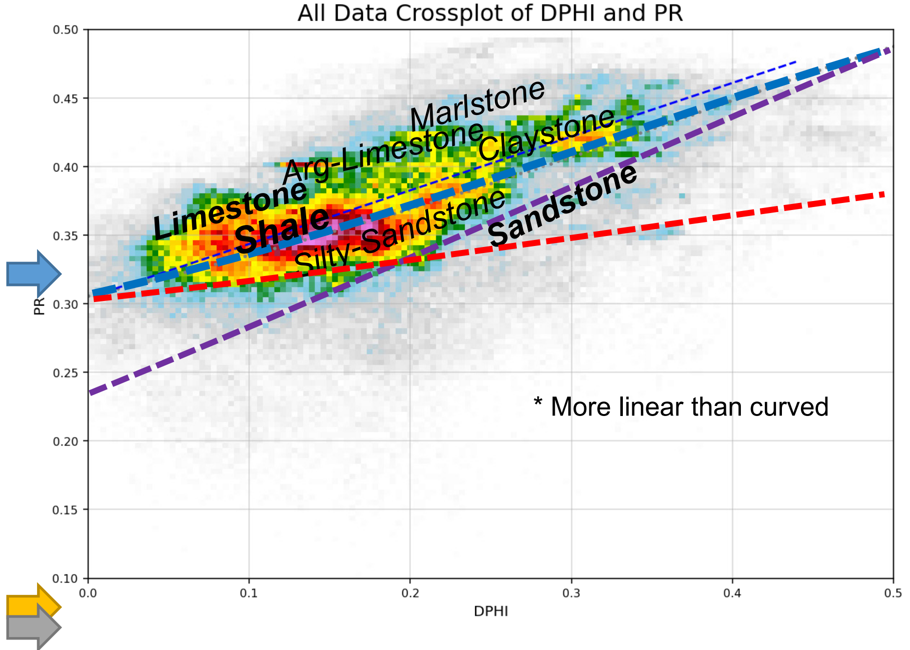
Lambda-Rho Mu-Rho



Rock Physic Displays (Linear in Vp, Vs & ρ   Curved in K, μ, & σ*)







Bulk & Shear modulus estimated using isotropic relationship to Vp, Vs and RHOB. Poisson Ratio estimate using Vp & Vs.

$$K = \rho\left(V_p^2 - {}^{4}/_{3}\, V_s^2\right) \qquad \mu = \rho V_s^2$$

$$\sigma = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - 2V_s^2\right)}$$

Conclusion – Future work

- The data has variation in parameters from published trends
- Correctly estimating porosity is one of the critical factors
- Quantification of rock properties for each rock type and mineralogy will be part of the next report
- Application of physics-informed parameters part thesis

Petrophysical Log Properties

Information compiled from Schlumberger, 1989, 1990, 2003; Baker, 2002; Castagna, 1985, 1993; Mavko 1998,Crain2000)

Minerals	Density gm/cm^3	V_{Pma} m/sec	V_{Sma} m/sec	DT (logs us/ft)	DT (logs us/m)	DTS (logs us/ft)	DTS (logs us/m)	Vp/Vs	Ip	1-V_{P90}/V_{Pma} ε	GR	P_e	K (%)	U (ppm)	Φn(%) Ther.	Resistivity	Farads/m	Thermal Conductivity	Chemical Formula
Quartz	2.65	5779	3930	52.7	173	78	254	1.47	15.30	0.00	-	1.81	<0.15	<0.5	-4.0	300-5x 10^{3}	4.65	7.8	SiO_2
Calcite	2.71	6500	3372	47	154	90	297	1.93	17.62	0.08	-	5.08	< 0.1	13.79	0.0	5000- 10^{7}	7.50	3.3	$CaCO_3$
Dolomite	2.87	7080	3909	43	141	78	256	1.81	20.28		-	3.14	0.1-0.3	9.00	2.0	500- 10^{5}	6.80	5.1	$CaCO_3MgCO_3$
Anhydrite	2.97	5640	3110	54	177	98	322	1.81	16.76		-	5.07		14.95	-0.7	1000- 10^{4}	6.3	5.3	$CaSO_4$
Halite	2.10	4620	2710	66	216	118	387	1.70	9.70		-	4.67		9.50	-1.8	10^{5}- 10^{7}	6.0	6.5	NaCl
Gypsum	2.33	5880	2770	52	170	110	361	2.12	13.69		-	3.80		9.40	57.5	10-1.2x 10^{2}	4.1	3.1	$CaSO_4(H_2O)_2$
Feldspars - Alkali	2.55	4420	2638	69	226	116	379	1.68	11.28		~220	2.9	11.8-14	7.20	-1.1	10^{3}	5.2	2.3	$KAlSi_3O_8$
Feldspars - Average	2.62	4690	2390	65	213	128	418	1.96	12.29										
F - Plagioclase (Albite)	2.60	6740	4110	45	148	85	279	1.64	17.51		~200	1.7	0.58	4.40		10^{3}	5.2		$NaAlSi_3O_8$ (Albite)
F - Plagioclase (Anorthite)	2.76	7690	4925	40	130	62	203	1.56	21.19		~200	3.1		8.60		10^{3}	5.2		$CaAl_2Si_2O_8$ (Anorthite)
Kaolinite	2.53	3020	1410	101	331	216	709	2.14	7.63	0.35	80-130	1.6	<0.8%	3.95	41.1	10^{1}	5.8	2.8	$Al_4Si_4O_{10}(OH)_8$
Illite	2.67	4320	2540	71	231	120	394	1.70	11.52	0.27	250-300	3.0	>3%	8.71	12.4	10^{1}	5.8	1.8	$K_{1-1.5}AL_4(Si_{7-6.5},AL_{1-1.5})O_{20}(OH)_4$
Montmorillonite/Smectite	2.32	5060	2770	60	198	110	361	1.83	11.74		150-200	1.9	0-5%	4.18	17.0	10^{1}	5.8	1.9	$(Ca,Na)_7(AL,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4(H_2C$
Chlorite	2.83	3400	1600	90	294	191	625	2.13	9.61		180-250	5.8	<0.8%	17.48	>32	10^{1}	5.8	4.2	$(Mg,Fe,AL)_6(Si,AL)_4O_{10}(OH)_8$
Anthractice Coal	1.51	2900	1357	105	345	225	737	2.14	4.39			0.2		0.23	41.4	10- 10^{3}		0.6	$CH_{.358}N_{.009}O_{.022}$
Bituminous Coal	1.30	2540	1184	120	394	257	845	2.15	3.29			0.2		0.21	>60				$CH_{.793}N_{.015}O_{.078}$
Lignite	1.16	2038	942	150	491	324	1062	2.16	2.36			0.2		0.24	54.2	9-2x 10^{2}			$CH_{.849}N_{.015}O_{.211}$
Basalt	2.75	5950	2600	51	168	117	385	2.29	16.39		60.0	4.0	1.13	0.40	4.4	300- 10^{3}		2.70	
Chalk	2.10	2600	1300	117	385	234	769	2.00	5.46		-	5.1	< 0.1	13.79	0.0	50- 10^{2}			$CaCO_3$
Granite	2.56	6000	3300	51	167	92	303	1.82	15.36		220.0	3.0				1000- 10^{6}		4.54	SiO_2(60-70%) a little of Al_2O_3,CaO,MgO a
Mixed Rock Lithology																			
Clay (Average)	2.68	3400	1600	90	294	191	625	2.13	9.10		~150	3.4	3.42			20- 10^{2}		2.57	
Shale	1.8-2.7	2616		63-170						0.12		3.5	1.6-4.2		9-45	50- 10^{3}		2.19	
Feldspars - Average	2.62	4690	2390	65	213	128	418	1.96	12.29		200	2.5			2.50	10^{2}			
Unconsolidated Sandstone	2.65	5180	3730	58.8	193				13.73							10^{2}			
Clean Sandstone (p10%)	2.57	5750	3730	53.0	174	82	268	1.54	14.78	0.00	15-30	1.7	<1.2	4.79		50- 10^{2}		4.87	
Dirty Sandstone (p10%)	2.55	5950	3870	51.2	168	79	258	1.54	15.15			2.7	0.7-3.8			10^{3}		2.70	
Conglomerate	2.57	5950	3870	51	168	79	258	1.5	15.2	0.00	25.0	2.7				10^{4}			
Limestone	2.63	6420	3400	47.5	156	90	294	1.89	16.85	0.08	10-20	5.0	<1.0	<0.1		5000- 10^{5}		4.11	
Dolomite (P>5.5%)	2.77	7000	4000	43.5	143	76	250	1.75	19.36		8-15	3.14	1.5-10	0.1-0.3		500- 10^{3}		7.30	
Dolomite (P<5.5%)	2.85	7000	4000	43.5	143	76	250	1.75	19.95			3.05	1.5-10	0.1-0.3		1000- 10^{4}			

Rock Physic Properties

Minerals	VPma m/sec	VSma m/sec	Density kg/m3	Bulk modulus K (Gpa)	Poisson Ratio σ*	Shear modulus μ (Gpa)$^+$	Lamb constant μ (Vp,Vs)	Vp from K, μ, & ρ	Vs from μ, & ρ	Vp/Vs From Poisson Ratio	Vp/Vs from Logs	Bulk modulus K from Vp & Vs	Poisson Ratio σ From Vp & Vs	Lamb constant μ from Vp & Vs	Lamb constant μ from K & σ
Quartz	5779	3930	2647	37.0	0.08	44.4	6.6	6028	4097	1.48	1.47	33.9	0.07	40.9	43.8
Calcite	6500	3372	2710	71.8	0.31	30.6	52.9	6447	3361	1.92	1.93	73.4	0.32	30.8	30.5
Dolomite	7080	3909	2865	86.5	0.24	48.8	56.1	7272	4126	1.72	1.81	85.3	0.28	43.8	53.6
Anhydrite	5640	3110	2973	57.1	0.28	30.4	37.0	5730	3198	1.80	1.81	56.2	0.28	28.8	30.2
Halite	4620	2710	2100	24.8	0.25	14.9	14.0	4610	2664	1.73	1.70	24.3	0.24	15.4	14.9
Gypsum	5880	2770	2328	40.0			44.8				2.12	56.7	0.36	17.9	
Feldspars - Alkali	4420	2638	2551		0.25		14.3				1.68	26.2	0.22	17.8	
Feldspars - Average	4690	2390	2620	37.5	0.32	15.0	27.7	4685	2393	1.94	1.96	37.7	0.32	15.0	15.3
F - Plagioclase (Albite)	6740	4110	2598	66.0	0.28	26.3	30.2	6237	3182	1.80	1.64	59.5	0.20	43.9	34.9
F - Plagioclase (Anorthite)	7690	4925	2755				29.3			1.41	1.56	73.8		66.8	
Kaolinite	3020	1410	2525	17.8	0.36	4.7	13.0	3087	1364	2.14	2.14	16.3	0.36	5.0	5.5
Illite	4320	2540	2666	32.4	0.24	14.0	15.4	4377	2292	1.71	1.70	26.8	0.24	17.2	20.4
Montmorillonite/Smectite	5060	2770	2320	29.0	0.21	7.9	23.8	4128	1845	1.65	1.83	35.7	0.29	17.8	20.9
Chlorite	3400	1600	2828	22.5	0.36	7.1	18.2	3362	1585	2.14	2.13	23.0	0.36	7.2	6.9
Anthractice Coal	2900	1357	1513	9.4	0.38	4.4	7.2	3177	1705	2.27	2.14	9.0	0.36	2.8	
Bituminous Coal	2540	1184	1295	4.7	0.35	1.8	4.7	2337	1179	2.08	2.15	5.9	0.36	1.8	
Lignite	2038	942	1160	2.5	0.38	0.9	2.8	1786	881	2.27	2.16	3.4	0.36	1.0	
Basalt	5950	2600	2754	58.5	0.20	4.0	60.3	4814	1205	1.63	2.29	72.7	0.38	18.6	43.9
Chalk	2600	1300	2100	9.0	0.35	3.2	7.1	2513	1234	2.08	2.00	9.5	0.33	3.5	3.0
Granite	6000	3300	2560	91.0	0.31	28.0		7080	3307	1.91	1.82	55.0	0.28	27.9	39.6
Mixed Rock Lithology															
Clay (Average)	3400	1600	2677	21.8	0.35	6.9	17.2	3405	1608	2.08	2.13	21.8	0.36	6.9	7.3
Shale															
Unconsolidated Sandstone	5180	3730	2650	38.5	0.14	36.9	-2.6	5753	3732	1.55	1.39	21.9	-0.04	36.9	
Clean Sandstone (p10%)	5750	3730	2570	38.5	0.14	36.9	13.5	5842	3789	1.55	1.54	37.3	0.14	35.8	
Dirty Sandstone (p10%)	5950	3870	2547	40.9	0.13	39.7	13.9	6070	3948	1.53	1.54	39.3	0.13	38.1	
Limestone	6420	3400	2625	70.0	0.31	31.3	47.5	6524	3453	1.91	1.89	67.7	0.31	30.3	
Dolomite (P>5.5%)	7000	4000	2765	79.0	0.26	45.6	47.0	7111	4061	1.76	1.75	76.5	0.26	44.2	
Dolomite (P<5.5%)	7000	4000	2850	79.0	0.26	45.6	48.5	7004	4000	1.76	1.75	78.9	0.26	45.6	

CREWES

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