5th Canadian Conf. Earthquake Engineering / Ottawa / 1987 / 5ème Conf. Canadienne Génie Sismique

The impact of reservoir area lithology on the temporal characteristics of reservoir triggered seismicity

David Amick, Frederic Snider, Samir Khoury & Peter Hansen
Ebasco Services, Inc., Greensboro, N.C., USA

ABSTRACT: Review of worldwide cases of Reservoir Triggered Seismicity (RTS) suggests that reservoir area lithology can not be used as a predictive tool to estimate the likelihood of RTS or its maximum magnitude. However, at reservoirs where RTS does take place, empirical data suggests that local lithology may impact on how long after impoundment the first and largest RTS events occur. This observation suggests that reservoir lithology could possibly be used to better define a "window of RTS risk" at new or recently impounded reservoirs, when seismic monitoring would be most appropriate.

1 INTRODUCTION

Macroseismic earthquake activity following reservoir impoundment has been documented at many reservoirs worldwide. This phenomenon, which we refer to as Reservoir Triggered Seismicity (RTS), is defined as the demonstratable temporal or spatial association of macroseismicity with reservoir impoundment or water level fluctuations. Further, post-impoundment levels of seismicity in the immediate vicinity of the reservoir must exceed pre-impoundment levels. RTS was first reported following the impoundment of Lake Meade in the 1930's (Carder, 1945), and while very few cases of RTS have been associated with damage, at over a dozen reservoirs the largest triggered earthquake has equaled or exceeded magnitude 5.0.

The largest RTS event to date is the magnitude 6.3 earthquake that occurred at Koyna Dam, in western India. This event caused significant damage to the dam and resulted in the loss of over 200 lives in nearby towns and villages (Gupta and Rastogi, 1976).

Previous investigators have searched for correlations of RTS with reservoir depth, reservoir volume, local geology, stress regime and the presence or absence of known faults (Stuart-Alexander and Mark, 1976; Packer et al., 1979). To date, a significant correlation of RTS has been found only for reservoir depth and reservoir volume, with a higher rate of RTS occurrence found for reservoirs greater than 80 to 90 meters in depth and/or those with capacities exceeding 7,000 to 10,000 million cubic meters.

As shown on Figure 1, of the approximately 250 reservoirs greater than 90 meters in depth and/or exceeding 10,000 million cubic meters capacity, 30 (more than 1 in 10) are associated with RTS. In contrast, the 7 cases of RTS associated with reservoirs shallower than 90 meters, or less than 10,000 million cubic meters represent less than 1/10 of 1 percent of the total number of reservoirs in this category. Clearly, reservoir depth and volume seem to have a significant impact on the likelihood of RTS. However, while deep and large reservoirs appear to be more likely to be associated with RTS, the largest RTS event to date occurred at a reservoir that is considered neither very deep or very large (Koyna, number 20, Figure 1).

Modeling studies indicate that the added shear stress due to the direct load of the water in even the largest reservoir is at least two orders of magnitude too small to fracture intact rock (Gough and Gough, 1970, Snow, 1972). Similarly, changes in effective stress associated with increased pore

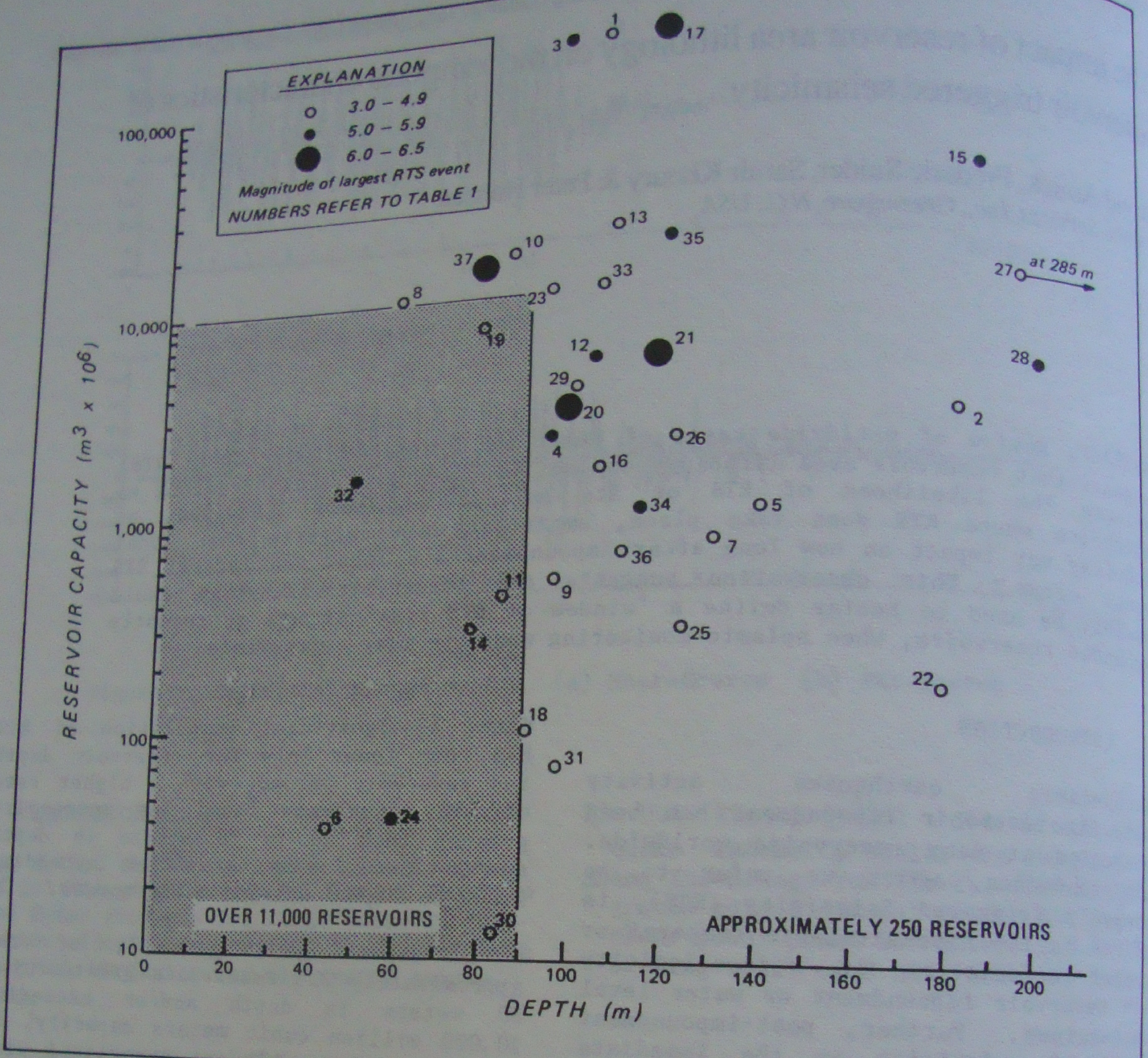

Figure 1. Reservoir Depth and Volume for 37 Cases of Reservoir Triggered Seismicity. *(modified from Packer et. al., 1979).*

pressures, due to the hydrologic impact of a very deep reservoir, are about an order of magnitude too small to cause new fractures (Whithers and Nyland, 1978 and Bell and Nur, 1978).

Therefore, on the basis of laboratory studies, theoretical modeling and empirical data, it is generally thought that at reservoirs where RTS occurs, the shallow crust within the hydrologic regime of the reservoir must be sufficiently stressed prior to impoundment such that increases in stress due to reservoir load, coupled with changes in effective stress brought about by elevated pore pressures, are sufficient to trigger the release of ambient or residual stress along pre-existing planes of weakness.

This model suggests that even small shallow reservoirs could trigger seismicity given sufficient levels of ambient stress and the presence of favorably oriented preexisting faults. Based on recent investigations (Talwani and Acre, 1985), it is becoming increasingly evident that the diffusion of increased pore pressures associated with reservoir filling and the resulting changes in effective stress play a primary role in triggering of RTS.

Since the rate of diffusion of pore pressure is directly related to the effective permeability of the materials beneath and adjacent to the reservoir, it is reasonable to suspect that variations in rock types (with their associated differences in effective permeability) would be reflected in the temporal characteristics of reservoir triggered seismicity. To test this hypothesis information regarding the local lithology and data on the time of reservoir impoundment, the time of first RTS event and the time of maximum RTS event was compiled for 37 worldwide cases of RTS. The information included in Table 1 was derived primarily from Gupta and Rastogi (1976), Packer et al. (1979), Perman et al. (1983), Amick and Snider (1985), Ebasco Services Inc. (1985), and Gupta (1985).

As noted previously, reported cases of RTS were included in our study if there was temporal and/or spatial association of macroseismicity with reservoir impoundment or water level fluctuations and where post-impoundment levels of seismicity in the immediate vicinity of the reservoir exceed pre-impoundment levels. Based on available site specific geologic information, the predominant lithology in the epicentral region at each reservoir associated with macroseismic RTS was characterized as:

- carbonate
- clastic
- volcanic
- metamorphic/crystalline

Where more than one rock type was present in the region, the reservoir area lithology was characterized by the rock type present in the RTS epicentral area. In cases where this could not be determined the reservoir area lithology was characterized as the most common rock type present.

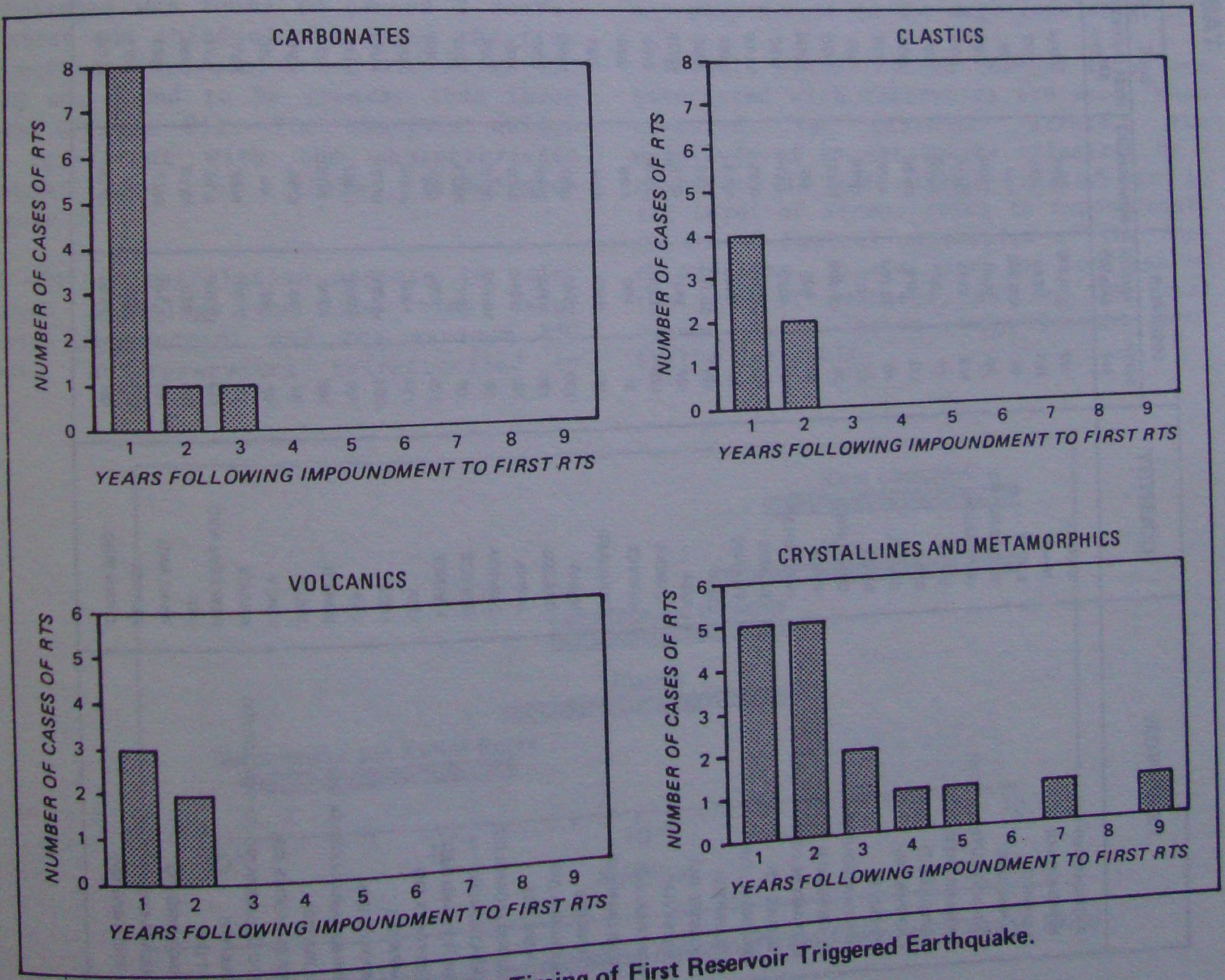

Figure 2. Impact of Lithology on Timing of First Reservoir Triggered Earthquake.

TABLE 1

RESERVOIR	COUNTRY	RESERVOIR		DATE OF			$RTS_{(1st)} - t_0$	$RTS_{(max)} - t_0$	MAGNITUDE OF $RTS_{(max)}$	RESERVOIR AREA LITHOLOGY
		DEPTH (m)	VOLUME ($m^3 \times 10^6$)	IMPOUNDMENT t_0	FIRST RTS EVENT $RTS_{(1st)}$	LARGEST RTS EVENT $RTS_{(max)}$	MONTHS	MONTHS		
AKOSOMBO (1)	GHANA	109	148,000	5/64	11/64	11/64	6	6	INTENSITY V	COARSE CLASTICS
ALMENDRA (2)	SPAIN	185	2649	4/71	1/72	7/72	9	15	3.2	CRYSTALLINES
ASWAN (3)	EGYPT	90	160,000	64	78	11/81	168	215	5.2	CRYSTALLINES
BENMORE (4)	NEW ZEALAND	96	2040	12/64	2/65	7/66	2	19	5.0	COARSE CLASTICS
BLOWERING/TAIBINGO (5)	AUSTRALIA	142	2559	5/71	6/71	1/73	1	20	3.5	CRYSTALLINES
CAMARILLAS (6)	SPAIN	43	37	11/60	3/61	4/64	4	41	4.1	CARBONATES
CANELLES (7)	SPAIN	132	678	10/60	6/62	6/62	20	20	4.7	CARBONATES
CAPIVARA (8)	BRAZIL	60	10,500	4/76	6/76	3/79	2	35	4.4	VOLCANICS
CENAJO (9)	SPAIN	97	472	11/60	3/61	11/65	4	60	4.2	CARBONATES
DANJIANGKOU (10)	CHINA (PRC)	88	20,900	11/67	1/70	11/73	37	60	4.7	METAMORPHICS
EL GRADO (11)	SPAIN	85	400	66	12/66	12/66	~6	6	INTENSITY IV	CARBONATES
EUCUMBENE (12)	AUSTRALIA	106	4761	6/57	5/59	5/59	23	23	5.0	METAMORPHICS
FURNAS (13)	BRAZIL	111	22,950	5/65	11/66	11/66	17	17	INTENSITY V	METAMORPHICS
GRANDVAL (14)	FRANCE	78	292	9/59	3/61	8/61	18	23	INTENSITY V	METAMORPHICS
HOOVER (15)	USA	191	36,703	5/35	9/36	3/40	16	58	5.0	FINE CLASTICS
JOCASSEE (16)	USA	107	1431	4/71	11/75	8/79	55	100	3.8	METAMORPHICS
KARIBA (17)	ZAMBIA	122	160,368	12/58	6/59	9/63	7	57	6.25	COARSE CLASTICS
KASTRAKI (18)	GREECE	91	100	1/69	3/69	3/69	2	2	4.6	CARBONATES
KHAO LAEM (19)	THAILAND	78	8500	6/84	7/84	1/85	1	7	4.1	CARBONATES
KOYNA (20)	INDIA	100	2780	6/61	10/63	12/67	28	78	6.3	VOLCANICS
KREMASTA (21)	GREECE	120	4750	7/65	8/65	1/66	1	6	6.3	CARBONATES
KUROBE (22)	JAPAN	180	199	3/60	8/61	8/61	15	15	4.9	CRYSTALLINES
MANICOUAGAN 3 (23)	CANADA	96	10,423	5/75	9/75	10/75	4	5	4.1	METAMORPHICS
MARATHON (24)	GREECE	60	41	10/29	7/31	7/38	33	103	5.75	METAMORPHICS
MONTEYNARD (25)	FRANCE	125	275	4/62	4/63	4/63	12	12	INTENSITY VII	CARBONATES
MOSSYROCK (26)	USA	124	1957	4/68	11/68	11/68	7	7	4.3	VOLCANICS
NUREK (27)	USSR	285	11,000	9/72	11/72	11/72	2	2	4.5	COARSE CLASTICS
OROVILLE (28)	USA	204	4400	11/67	6/75	8/75	91	93	5.7	METAMORPHICS
PARAIBUNA/PARAITINGA (29)	BRAZIL	102	4740	~9/75	1/77	11/77	~16	~26	3.2	METAMORPHICS
PIASTRA (30)	ITALY	84	13	6/65	10/65	4/66	4	10	4.4	METAMORPHICS
PIEVE DI CADORE (31)	ITALY	98	69	49	1/50	1/50	< 12	12	INTENSITY V	CARBONATES
PORTO COLUMBIA/VOLTA GRANDE (32)	BRAZIL	50	3760	4/73	11/73	2/74	7	10	5.1	VOLCANICS
PUKAKI (33)	NEW ZEALAND	108	10,500	1/76	4/77	12/78	15	35	4.6	COARSE CLASTICS
SWIFT (34)	USA	116	932	10/58	7/60	9/61	21	35	5.0	VOLCANICS
SRINAGARIND (35)	THAILAND	133	17,745	8/77	4/83	4/83	68	68	5.9	CRYSTALLINES
VOUGLANS (36)	FRANCE	112	605	68	6/71	6/71	~36	36	4.4	CARBONATES
XINFENGJIANG (37)	CHINA (PRC)	80	13,896	10/59	11/59	3/62	1	33	6.0	CRYSTALLINES

3 Impact of Reservoir Lithology

3.1 Temporal Patterns of RTS Activity

As shown on Figure 2, at reservoirs characterized as carbonate, the time delay between impoundment and the first RTS event was found to be generally less than one year. This is consistent with the karstic nature of many limestones, allowing for rapid pore pressure diffusion.

Similar lag times between impoundment and the first RTS event were determined for reservoirs characterized by volcanic and clastic lithologies (Figure 2). It is significant to note that at reservoirs characterized as carbonate, volcanic or clastics the time lag between impoundment and the first RTS event was in no case greater than three years.

The time delay between impoundment and the first RTS event at reservoirs characterized as metamorphic/crystalline was found to be slightly longer. The mean time delay between impoundment and the first RTS event at reservoirs characterized by metamorphic/crystalline lithologies was found to exceed 3 years. In about one third of the cases the time lag between impoundment and the first RTS event was found to be greater than three years (Figure 2). The observed delays are consistent with the characteristic permeabilities of these lithologies (Figure 3).

A similar correlation appears to exist between lithology and the time delay between impoundment and the maximum RTS event. At reservoirs characterized by carbonate, volcanic, or clastic lithologies the mean time delay between impoundment and the maximum RTS event was found to be less than 3 years and in only one instance was the time delay found to be greater than 5 years.

In contrast, at reservoirs characterized by metamorphic or crystalline lithologies the time delay was found to be longer than that observed at other reservoirs (Figure 4). The mean time delay between impoundment and the maximum RTS event at these reservoirs was found to exceed 4 years. In more than one third of the cases the observed time delay was equal or greater than 5 years.

3.2 Magnitude of Largest RTS Earthquake

A comparison of lithology vs magnitude of largest RTS earthquake is presented on Figure 5. As shown, magnitude 6 or greater RTS earthquakes have been associated with each of the four main lithologic types. Further, smaller magnitude earthquakes are also associated with each reservoir type. These observations suggest that lithology does not play a role in the magnitude of RTS.

Rather, since induced changes in stress associated with reservoirs are small when compared to tectonic stress, the magnitude of an earthquake triggered by a reservoir is more likely related to 1) the level of stress prior to impoundment, 2) the mechanical properties of the zone of weakness, 3) the size and location of the zone of weakness, and 4) the areal extent of the stress change brought about by the reservoir.

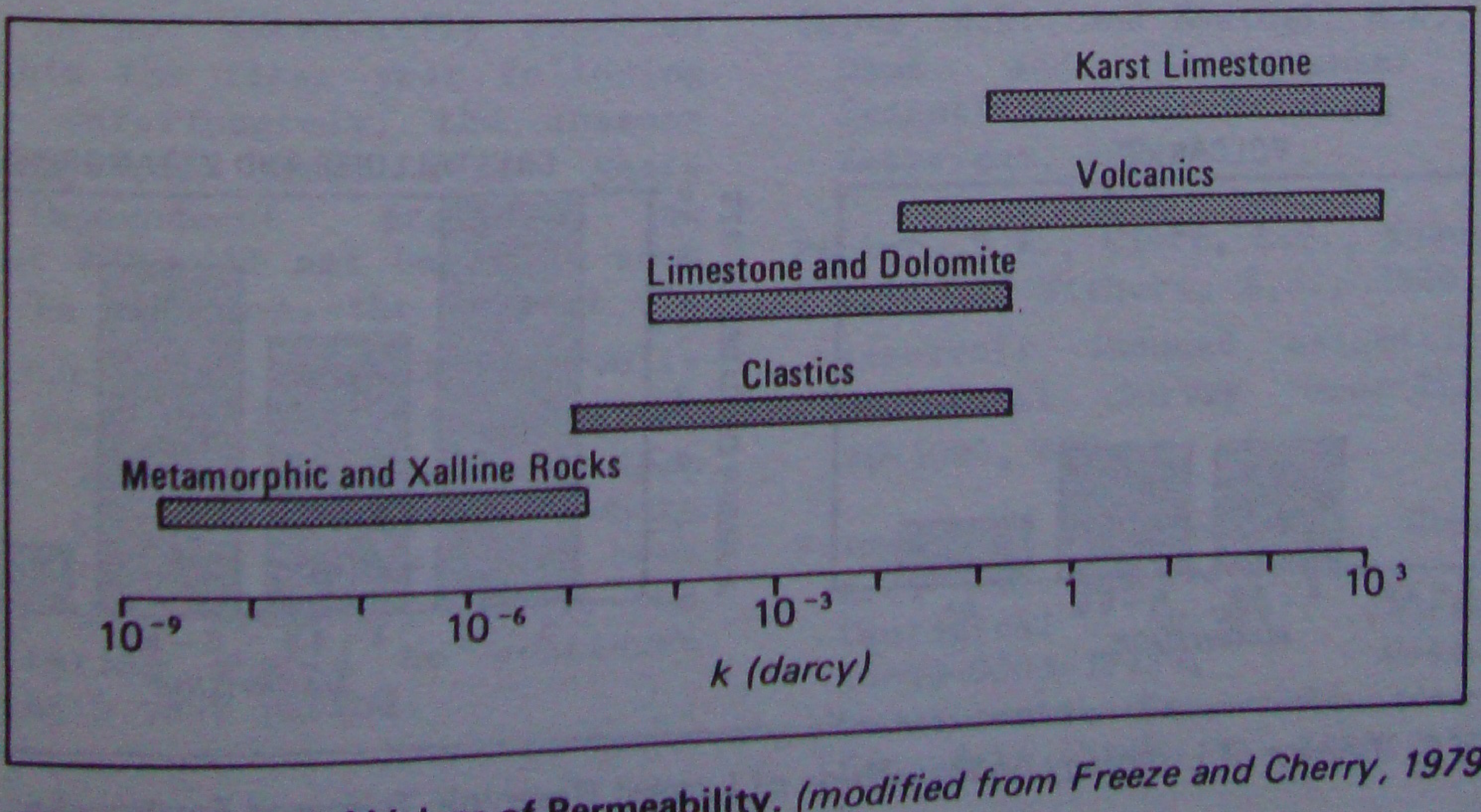

Figure 3. Range of Values of Permeability. *(modified from Freeze and Cherry, 1979)*

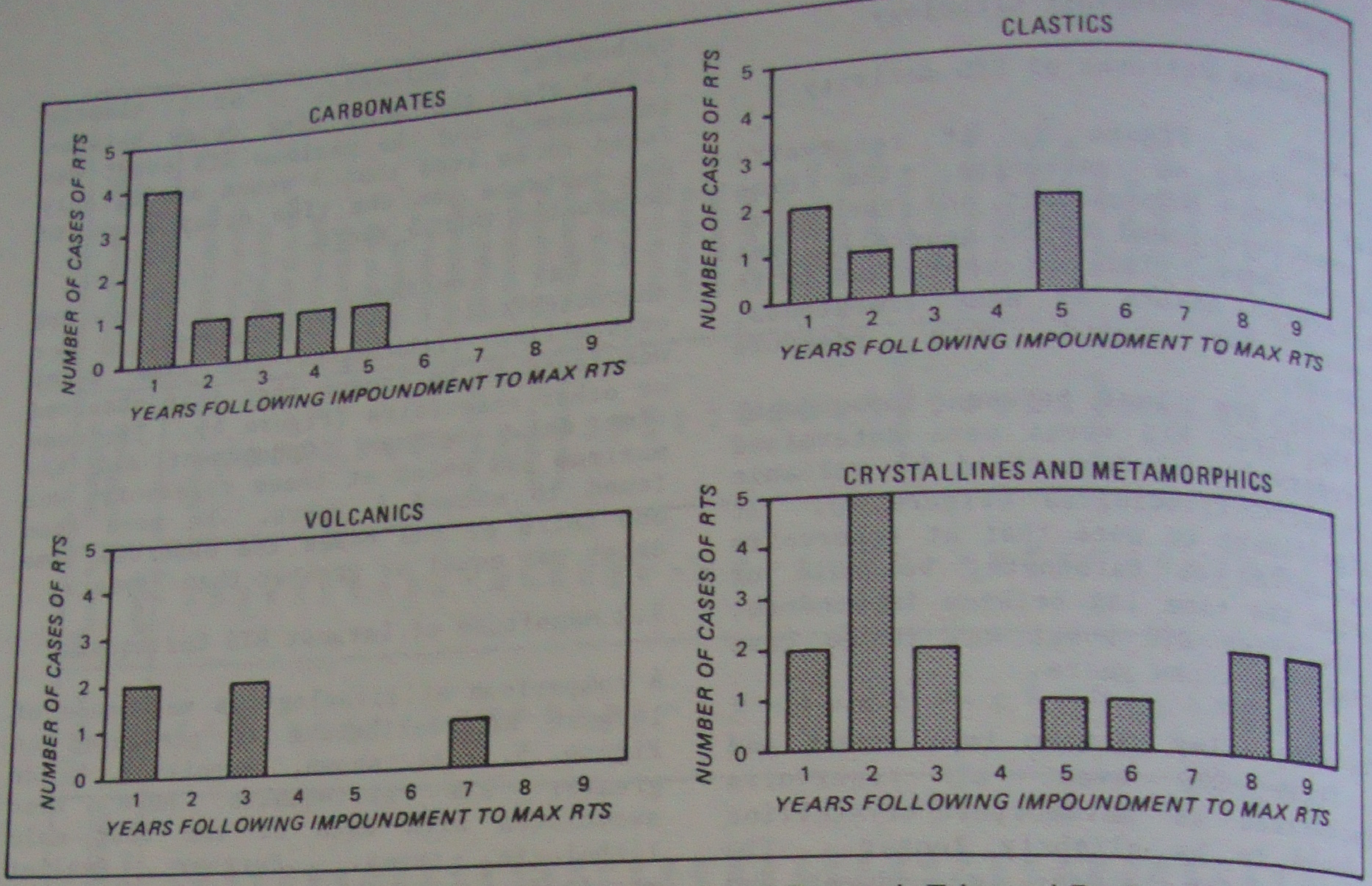

Figure 4. Impact of Lithology on Timing of Maximum Reservoir Triggered Earthquake.

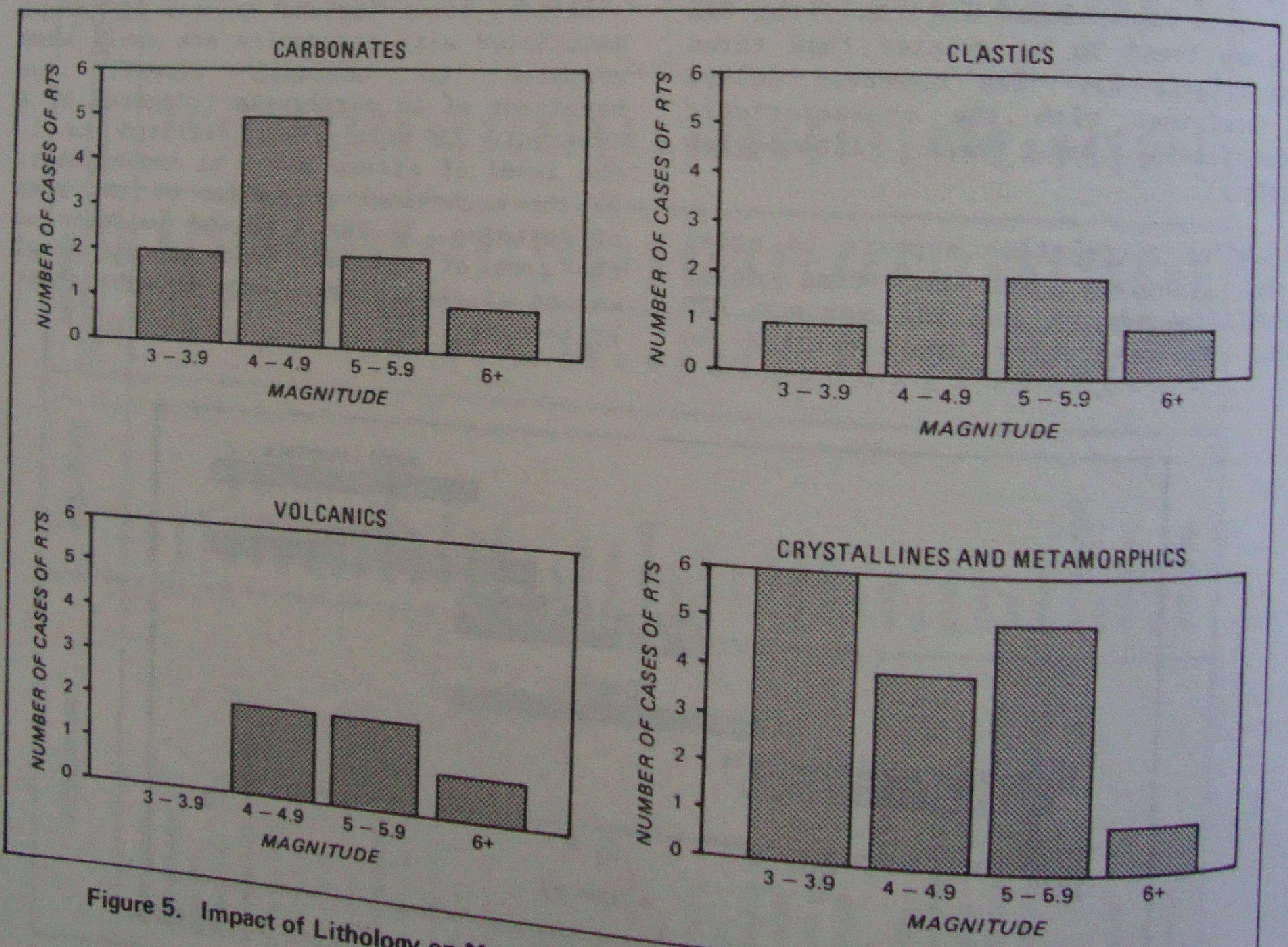

Figure 5. Impact of Lithology on Magnitude of Largest Reservoir Triggered Earthquake.

4 Discussion

While characterization of reservoir area lithology does not appear to be useful as a predictive tool to estimate the likelihood of RTS or its maximum magnitude, the data presented in this paper suggest that reservoir lithology, which can be used as a general indication of reservoir area permeability, might be used to define the "window of RTS risk" at new or recently impounded reservoirs, when seismic monitoring would be most beneficial and appropriate.

For example, in the case of a reservoir characterized by carbonate, clastic or volcanic lithologies, if RTS activity is to occur, the empirical data presented here suggests that initial RTS will most likely occur within one year following impoundment and at the latest within three years after impoundment. This constitutes the period when seismic monitoring would be most appropriate. If no activity has been observed by the end of the third year, the likelihood of RTS occurring in the future becomes decreasingly low, suggesting that continued seismic monitoring may be inappropriate.

If, on the other hand, RTS was observed during the first three years following impoundment, continued seismic monitoring might be in order. However, the empirical data presented here indicates that the maximum RTS event could be expected to occur within 5 years following impoundment, suggesting that reduced levels of seismic monitoring may be acceptable beyond that time.

Conversely, for reservoirs impounded in metamorphic or crystalline lithologies, initial RTS in not necessarily expected to occur within the first year following impoundment. Unfortunately, the absence of RTS during the first three years following impoundment provides no assurance that RTS will not begin at some later date. In addition, the largest RTS event has occurred at several reservoirs more than 5 years following impoundment. Consequently, for very large or deep reservoirs or reservoirs where pre-existing zones of weakness have been identified in close proximity to the dam seismic monitoring should be continued well beyond the 5 year period.

5 REFERENCES

Amick, D., and Snider, F., Seismicity associated with reservoirs impounded near Mount St. Helens - Association of Engineering Geologists, 28th Annual Meeting, Winston-Salem, N.C., October 7-11, 1985.

Bell, M.L., and Nur, A., 1978, Strength changes due to reservoir-induced pore pressure and stresses and application to Lake Oroville: Journal of Geophysical Research, v. 83, p. 4469-4483.

Carder, D.S., 1945, Seismic investigations in the Boulder Dam area, 1940-1944, and the influence of reservoir loading on earthquake activity: Seismological Society of America Bulletin, v. 35, p. 175-192.

Ebasco Services Inc., September 1985-September 1986 Seismic Monitoring of the Khao Laem Project Region prepared for the Electricity Generating Authority of Thailand (EGAT).

Freeze, R. Allan, and Cherry, John A., 1979, GROUNDWATER, Englewood Cliffs, N.J., Prentice-Hall, Inc.

Gough, D.I., and Gough, W.I., 1970, Load-induced earthquakes at Lake Kariba--II: Royal Astronomical Society Geophysical Journal, v. 21, p. 70-101.

Gupta, H.K., 1985, The present status of reservoir induced seismicity investigations with special emphasis on Koyna earthquakes: Tectonophysics, v. 118, p. 257-279.

Gupta, H.K., and Rastogi, B.K., 1976, Dams and earthquakes: Elsevier Scientific Publishing Company, Amsterdam, 229.

Packer, D.R., Cluff, L.S., Kneupfer, P.L. and Withers, R.J., 1980, Study of reservoir induced seismicity: U.S. Geological Survey Open-File Report 80-1090, 689 p.

Perman, R.C., Packer, D.R., Coppersmith, K.J. and Knuepfer, P.L., 1983, U.S. Geological Survey Contract No. 14-08-0001-19132, Woodward-Clyde Consultants, Ca., Collection of data for data bank on reservoir induced seismicity, final technical report.

Snow, D.T., 1972, Geodynamics of seismic reservoirs, in Proceedings of the Symposium on Percolation Through Fissured Rocks: Deutsche Gesellschaft fur Erd and Grundbau, Stuttgart, Germany, T2-J, p. 1-19.

Talwani, P., and Acree, S., 1985, Pore pressure diffusion and the mechanism of reservoir-induced seismicity: Pageoph (Pure and Applied Geophysics), v. 122 (1984/85), p. 947-965.

Withers, R.J., and Nyland, E., 1978, Time evolution of stress under an artificial lake and its implication for induced seismicity: Canadian Journal of Earth Sciences, v. 15, p. 1526-1534.