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A Bibliometric Analysis of Carbonate Paragenesis

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ABSTRACT - Carbonate rock deposits play an important role in the oil and gas industries because it is a good reservoir for hydrocarbon due to the porosity related to diagenesis and paragenesis processes which produce many pore types. Paragenesis is a mineral sequence that is formed in rocks or ore deposits. The analysis that is done to determine the paragenesis is Petrography analysis, Scanning Electron Microscopy, and Cathodoluminescence. This paper discussed the bibliometric analysis in paragenesis subjects using VOSviewer, Open Refine, and Tableau. The analysis showed a result of 987 articles published on the topic of paragenesis from 1999 until 2022 with 537 authors from 46 different countries and around 308 publications with the predefined keyword. VOS viewer could generate a few bibliometric maps such as Co-occurrence, Co-citation of authors and countries. It shows the correlation between each keyword in the bibliometric map showing topics related to paragenesis and also the relations between the country origins. It shows that paragenesis is an important subject to study in not only the ore deposits field but also needs to be used in oil and gas fields because the prospects for paragenesis in the science world are promising.

Keywords: carbonate, paragenesis, hydrocarbon, bibliometric map.

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INTRODUCTION

Earth's crust is mainly composed of sedimentary rocks that either turn as a form of carbonate rocks or are reduced as organic matter, the process of sedimentation burial could result in thermal reactions that produce hydrocarbons in liquid and gaseous form that usually come from organic-rich sediments with high content of carbons. That makes carbonaceous deposits one of the most important objects in oil and gas industries as well as the world's main energy sources (Birger et al., 2019). Carbonates are naturally formed as sediments or reefs mostly in marine environments with tropical and temperate seas, also as important mineral deposits. Not only that, but carbonate rocks also could be an excellent porous and permeable groundwater aquifer. That means the porosity in carbonate rocks is also an important object to analyze because we know that the fluid storage and transmission through the porosity pores could be influenced by the condition of the environment around during the burial processes of the rocks. Carbonate reservoirs may have a variation of pore system and it is necessary to understand the origin of it because from it can be collected the depositional characteristics data (Ahr, 2008). One of the factors that affects the carbonate reservoirs are diagenesis process that is usually associated with the geological structural systems such as faults and

fractures with the product of strong dolomitization silicification and dissolution. Those products are also a part of the paragenetic evolution of the diagenetic processes (Lima et al., 2020).

Diagenetic processes could also affect the porosity of the reservoir resulting in multiple pore types such as vuggy or some microporosity and the different relationship between the porosity. Meanwhile, Paragenesis is a term that is sometimes used as a reference to characteristics of ore mineral assemblages, or it can also be used as a sequential formation of associated minerals (Craig et al., 1994). Meanwhile, according to Britannica Encyclopedia, Paragenesis itself is a sequence of minerals that are formed in rocks or an ore deposit. Minerals in the same ore deposit can have several variations in the temperatures and pressure changes that affect the minerals and the chemical elements from the hydrothermal solution. In particular, the location of the ore deposit has been formed by more than one period of hydrothermal activity, which makes the paragenesis sequences more complicated. Even if the decision of this paragenesis is not too vital in ore and hydrocarbon exploitation paragenesis can be an important benefit to explain the geological history of the minerals deposits and to determine when hydrocarbon migrates and is placed inside the porosity of the reservoir (Dani, 2012).

Porosity is one of the important aspects in the petrophysical study and reservoir rock because through porosity we can determine the storage capacity of the original hydrocarbon in place inside the reservoir rock (Widarsono, 2014). Porosity can be evaluated by using petrography, image analysis, and core analysis. Porosity is also heavily controlled by mechanical and chemical compaction or diagenesis processes that can result in porosity reduction (Musu, 2007). Especially limestone porosity affects the quality of the reservoir rather than cementation, whether the pore system is vuggy, fractured, or connected system limestone reservoir porosity is much more complex than sandstone porosity (Widarsono, 2011) limestone reservoir tends to be influenced not only by the tectonic but also by the dissolution process associated with sea level change and also exchanging of ions that result in recrystallization and effects from hydrothermal circulation, which is why the pore structures in limestone reservoirs are complex and extremely challenging but also a good reservoir for hydrocarbon migration and placement (Usman, 2014).

Thin section, SEM (Scanning Electron Microscopy), and Cathodoluminescence are a very important step in analyzing the paragenetic evolution from the diagenetic processes and products. Hydrothermal flow also plays an important part in paragenesis, which could cause petroleum inclusion, and to testify the typical oil generation and migration because the hydrothermal flow, could create an alteration with a strong impact on the porosity, permeability, and heterogeneity of the host rocks. Usually carbonate reservoirs have quite an elaborate heterogeneous diagenetic evolution and interact with many fractures, which results in strong dolomitization, silicification, or dissolution. The figure below shows a paragenetic sequence interpreted from the calcite crusts in the northern Campos Basin, Brazil. Therefore, the paragenetic sequence has been divided into four stages, which are the Syngenetic, Eodiagenetic, Mesodiagenetic, and Hydrothermal phases (Figure 1) (Lima et al., 2020).

The application of paragenesis study in Indonesia is still relatively small one of the case examples is Ponorogo, East Java used the term paragenesis to point to the mineralization sequence. The analysis of the ore mineral deposit structure present in veins indicates that there are two phases of mineralization. The early phase of mineralization was related to hypogene processes meanwhile the second phase resulted in supergene enrichment processes (Table 1) (Hastuti and Wiwik, 2017).

From the case above show the use of paragenesis in the ore minerals fields it means that most publications about paragenesis in Indonesia are from the mineralogical discussion because the use of paragenesis in the oil and gas industries is still little unknown. However, apart from that, some cases discuss the use of paragenesis in the oil and gas field in Indonesia. This case example is from research with Jambak in 2016 that was done in the Miocene-aged carbonate reservoir rocks in the Northwest Java Basin. The research was done in a few formations of the Northwest Java Basin, which are the Middle Cibulakan Formation, Upper Cibulakan Formation, and Parigi Formation. Each of these formations had a different diagenesis and paragenetic sequence that is based on how the tectonic processes occur. The data used in this research were obtained from laboratory results from petrography analysis, SEM, XRD, Cathodolumination, and geochemistry analysis.

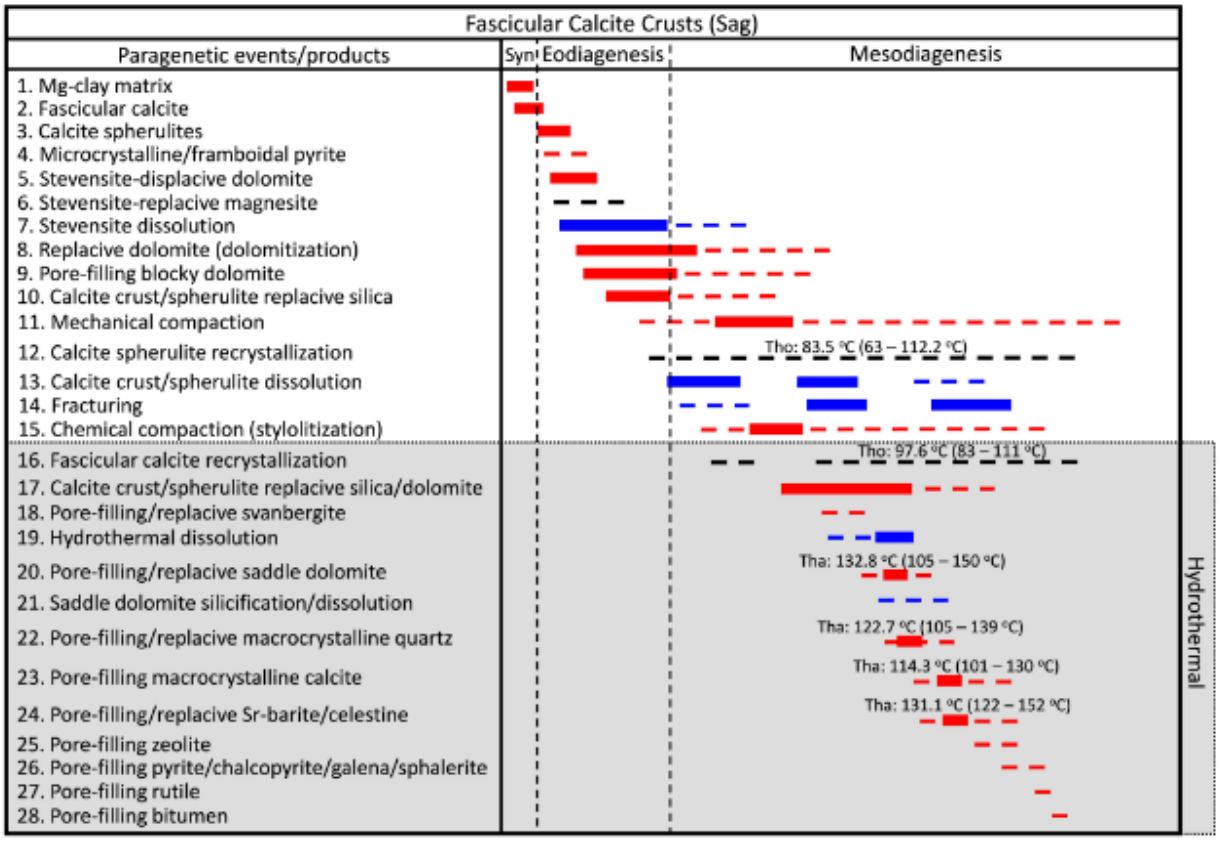

Figure 1
Paragenetic Sequences of calcite crusts in northern Campos Basin, Brazil. Thick lines show the intensity and abundance of the process, red lines show less porosity and blue lines show a porosity increase. Tha and Tho show the average homogenization temperature of primary aqueous and oil inclusions each. (Lima et al., 2020)

Table 1
Paragenesis in the study area, which is the Southern Mountain Range of Ponorogo, East Java (Hastuti and Wiwik, 2017)

ORE MINERAL	HYPOGENE (200 – 360°C) 400°C	300°C	200°C	100°C
Magnetite				
Pyrite				
Sphalerite				
Galena				
Chalcopyrite				
Bonite				
Arsenopyrite				
				SUPERGENE <125°C
Covelite				
Bornite				
Digenite				
Chalcosite				
Limonite				

In the Middle Cibulakan Formation, the early start of diagenesis or the syndepositional stage is shown from the cement, which is a marine deposited cement consisting of High-Magnesium calcite with radian or fibrous cement and then followed by a non-Fe calcite with isopachous cement and in this early stage the reservoir porosity is still good-very good. The next stage which is the Shallow Phreatic stage has a few processes that happen which as Karstification, Chemical and physical compaction that happen until the end of the diagenesis stage, Recrystallization, Dolomitization and a slight hydrocarbon placing in the reservoir with the porosity poor-good. Then the last stage of diagenesis which is the burial stage, starts to form a stylolite, fractures, and much more hydrocarbon placed inside the reservoir rock with poor-good porosity and in this last stage mainly formed because of the sediment overburden.

The Upper Cibulakan Formation mostly presents cementation of the non-Fe Calcite and allochems which are formed in the early stage (Syndepositional) and with reservoir porosity of good-very good. The next stage of diagenesis which is in the Shallow Phreatic regime occurs a few processes which are karstification, chemical, and physical compaction until the last stage of diagenesis, recrystallization, dolomitization, stylolite, and some oil placing with reservoir porosity of fair-good until the end of the diagenesis process. then the last stage, which is the burial stage, formed fractures and the continuous oil placed inside the porosity.

Meanwhile, in the Parigi Formation, the diagenesis process happened in a marine environment because the marine cement formed as a non-Fe fibrous radial calcite cement as a product of the early diagenesis stage, the next stage occurred some processes such as karstification which resulted in an aragonite dissolution then occur chemical compaction that formed a non-Fe Calcite cement as a filling in porosity, then physical compaction that happened until the end of diagenesis process, recrystallization, dolomitization, and then starting a formation of stylolite and oil placing. For the last stage as the end of the diagenesis, that is last fractures and oil placing start to decrease. The porosity of the reservoir from the start is still good-very good, then for the middle of the process, it reduces to fair-good then at the last stage the porosity goes up again from poor – very good. From the explanation of each formation above it can be concluded that the quality of the porosity from good to excellent and the permeability are affected by the depositional environment during the diagenesis process and also the tectonics that happened in the research can be one of the factors involved which resulted in oil placement inside the porosity.

METHODOLOGY

The data used in this analysis comes from articles contained in Scopus and ScienceDirect and also from a few open-access journal sites, which are systematically arranged to minimize possible errors when selecting articles according to the topic of the analysis (Deyer and Tranfield, 2009). This analysis is divided into lists of the occurrence network with the topic, country of origin, and the year the articles were published. Content Analysis is also measured quantitatively through many keywords (Ellegaard and Wallin, 2015).

The proposed method for this bibliometric analysis is structured and consists of four phases in stages which are determining the keywords or search criteria, data gathering and compilation, Data processing and refinement of the criteria, and analysis from the result to determine the development of paragenesis in the world especially in Indonesia to expand and develop the knowledge about paragenesis. The words used as search criteria and keywords are Paragenesis and Carbonate as a reference to the research topics. This part of the research allows the compilation of the basic data that will be used for the next analysis (Figure 2) (Hiatt, 2000).

RESULT AND DISCUSSION

After doing the search results about a geological term called “paragenesis”, show the study on this topic has produced a total of 987 publications for the period of 1999 to 2022. The number of publications shows an increase each year in the period investigated but experienced a decline every five years in 2001, 2006, and 2010 and also a decline every three years in 2013 and 2016. The analysis reveals that 1999 was the birth period of paragenesis. This result shows that paragenesis is a scientific field with an unstable number of publications and interest every year, unlike other general fields with stable publication numbers increasing each year. Therefore, the space for paragenesis studies is still potentially large for future studies.

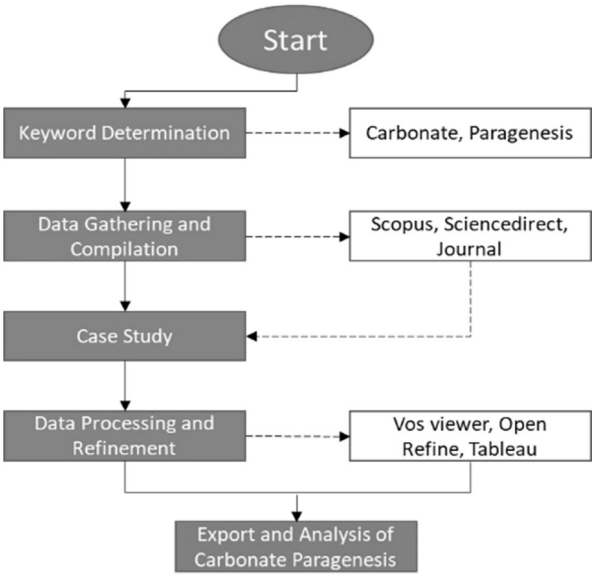

Figure 2
Diagram of the methodology used in this article

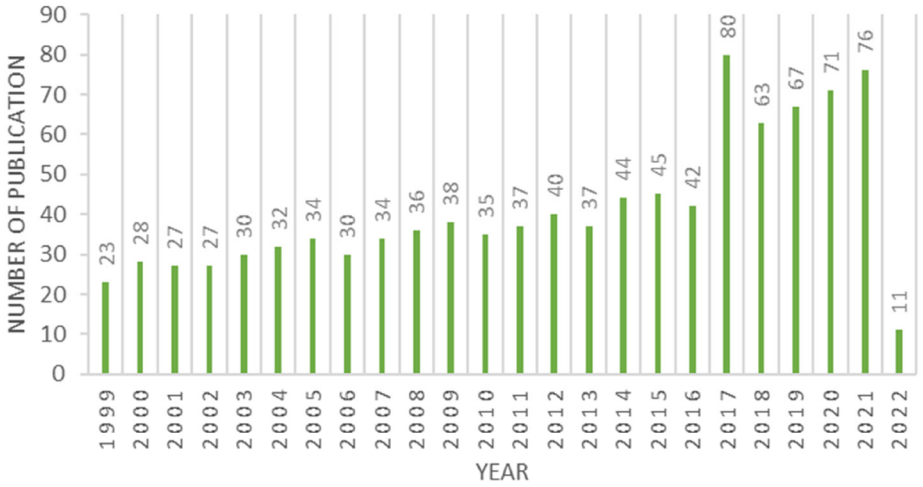

Figure 3
Distribution of Publications in Paragenesis year 1999-2022

Publications with 23 articles then experienced a publication increase in the next year reaching the peak publication in 2017 with 80 publications but then there was a decline in publications and then experienced a slow growth of publications in the year 2018 until 2021 and this year, 2022 there is only eleven publication (Figure 3). Meanwhile the term "Carbonate Paragenesis" showed 308 publications. 2017 was the birth year period for carbonate paragenesis with 70 articles but then declined to 46 in 2018 and then slowly increased each year until it reached the peak period in 2021 with 71 articles. In 2022 right now, there is only one publication yet with the hope that it will increase again (Figure 4).

Another thing that is the most important aspect to analyze is the number of citations of journals that discuss the same topic as the used keyword, which is paragenesis, and the country origin of the publications to determine which country is the most advanced and has the most publications in this study.

The figure below shows the percentage of document topics in paragenesis and citation analysis, the most cited publication was by deMelo et al with 60 citations, with the title Temporal evolution of the giant Salobo IOCG deposit, Carajás Province (Brazil): constraints from paragenesis of hydrothermal alteration and U-Pb geochronology. In this publication deMelo et al state that the paragenetic

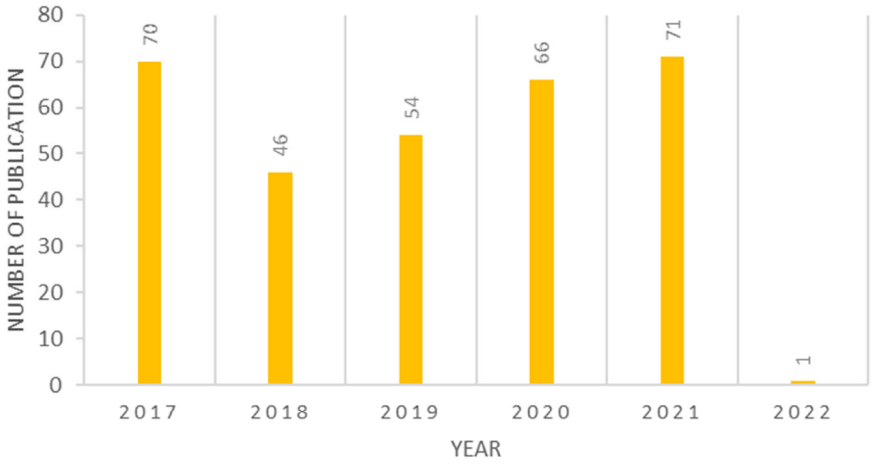

Figure 4
Distribution of Publications in Carbonate Paragenesis year 2017-2022

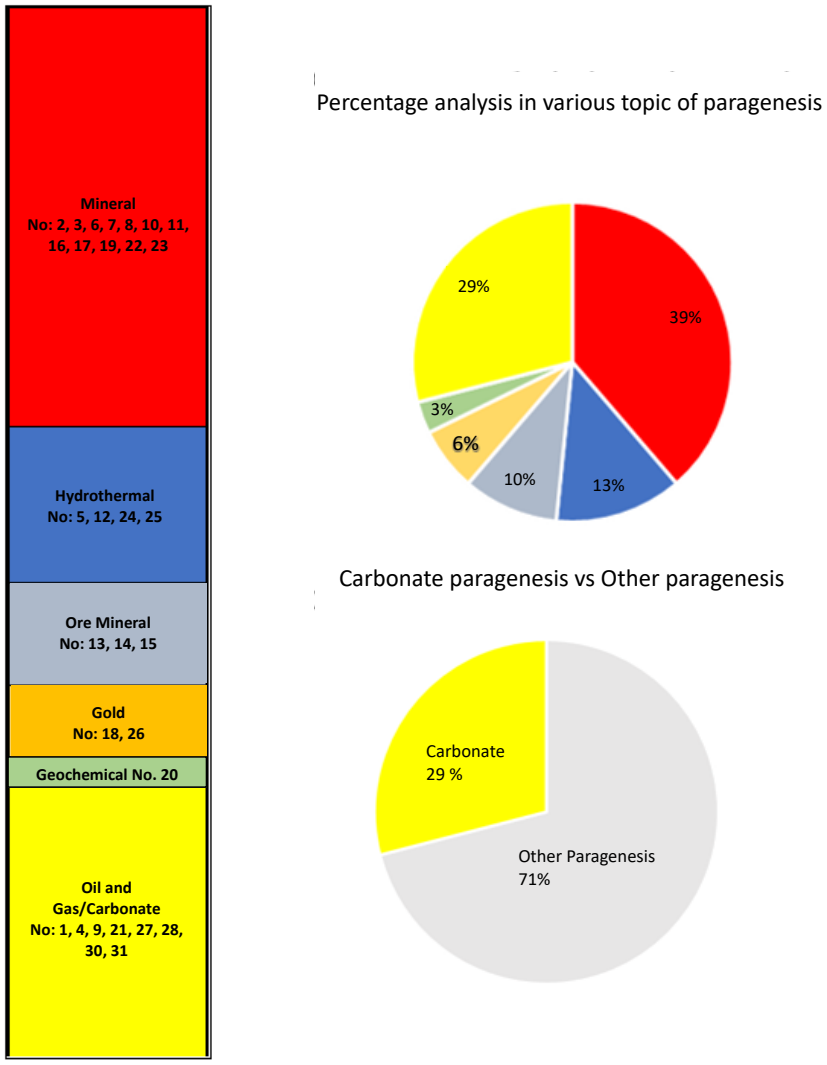

Figure 5
Paragenesis topic classification and percentage pie chart

sequence represents a decreasing temperature in the hydrothermal system that appeared from the hydrolytic alteration during or after the mineralization stage and also in this paper presents the new paragenetic data for the Salobo deposit with new insight on the temporal evolution of this IOCG (Iron oxide-copper-gold) Deposits which are economically important, these Salobo deposits are believed to be associated with the alkaline emplacement and crystallization of the deposit itself (deMelo et al., 2017).

Paragenesis has been widely used in many different areas of study, the figure above shows a rough percentage of paragenesis studies in different topics from the literature used. It has been categorized into a few classifications such as minerals, hydrothermal, ore mineral, gold, and oil and gas or in carbonate. The highest percentage can be found in the mineral's topic, which is 39%, and there are 12 out of 31 publications, it can also be divided again according to the method used in each research. The methods that are usually used generally are petrographic analysis, isotope analysis or mapping, SEM (Scanning Electron Microscope), and XRD (X-ray diffraction). But the specifically used can be found in the second highest percentage which is the oil and gas or carbonate topics with 29% (9 out of 31 publications) The special method used is Cathodoluminescence (CL) shows certain minerals components from the luminescence that appeared and lastly are fluorescence analysis or UVF (Ultra Violet Fluorescence) to detect the hydrocarbons or how oil dispersed inside the sample taken which can be seen from the visible light that emitted from the sample. Next are hydrothermal topics with 13% and there are 4 publications out of 31 publications. With 10% there are ore mineral topics with three publications and then followed by gold topic which is 6% with two publications and the last one is a geochemical topic with one publication and topic with the lowest percentage which is 3%. If the other paragenesis topics are combined as one and compared with the carbonate paragenesis it shows that there are still many studies that used paragenesis in the minerals, hydrothermal, ore, and others topics with 71% percentage rather than the carbonate field with 29% percentage (Figure 5).

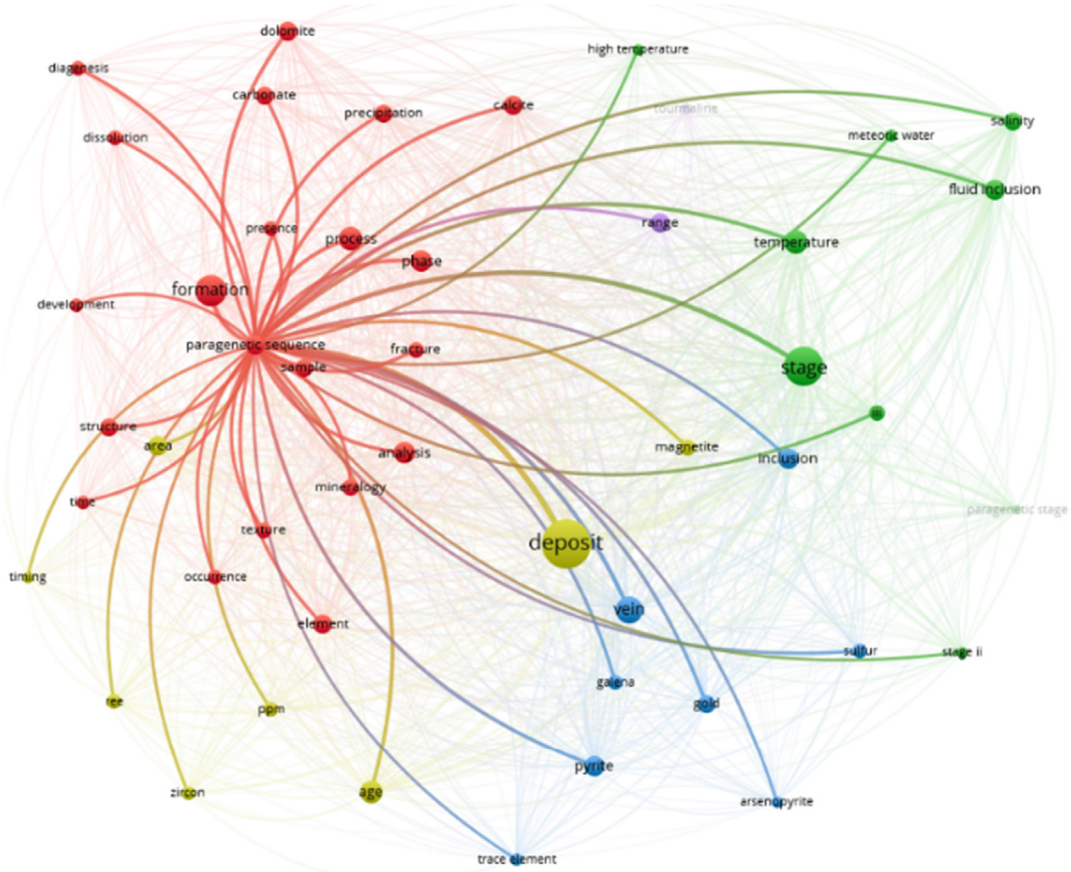

Figure 6
Co-occurrence bibliometric map of author keywords

In this step VOS viewer were used to determine and prepare the bibliometric map of author keywords and analyze the strong correlation between the keywords. The network resulted in 44 keywords that make up to five clusters (Figure 6) and the correlation shows through nodes and links. Keywords are represented by nodes and the bigger the node's size means that the relation with the main keyword is also very related and vice versa (Zupic and Čater, 2015). The most developed research area is Deposit in the yellow nodes where the research focuses on knowing mostly about the deposit of the energy resource. For example, Peng et al discuss in their publications the Formation mechanism of saddle dolomite hydrothermal fluid in the Middle-Upper Cambrian, he then explained that the Lower Cambrian Deposits of thick mudstone in Niutitang and Qiongzhusi Formations have multiple sets of volcanic detritus deposits which supplied the necessary material condition with fluid that are rich in ore and Mg^{+} (Peng et al., 2018). Meanwhile, another developed area that correlates with paragenesis is in the Paragenetic Sequence research area with red nodes that connected to a few other research areas such as Formation, Stage, Mineralogy, Deposits, etc. In Dongpu Depression, China showed that there is a heavy shale oil that was a product of biodegradation trapped in ferrous dolomite to know

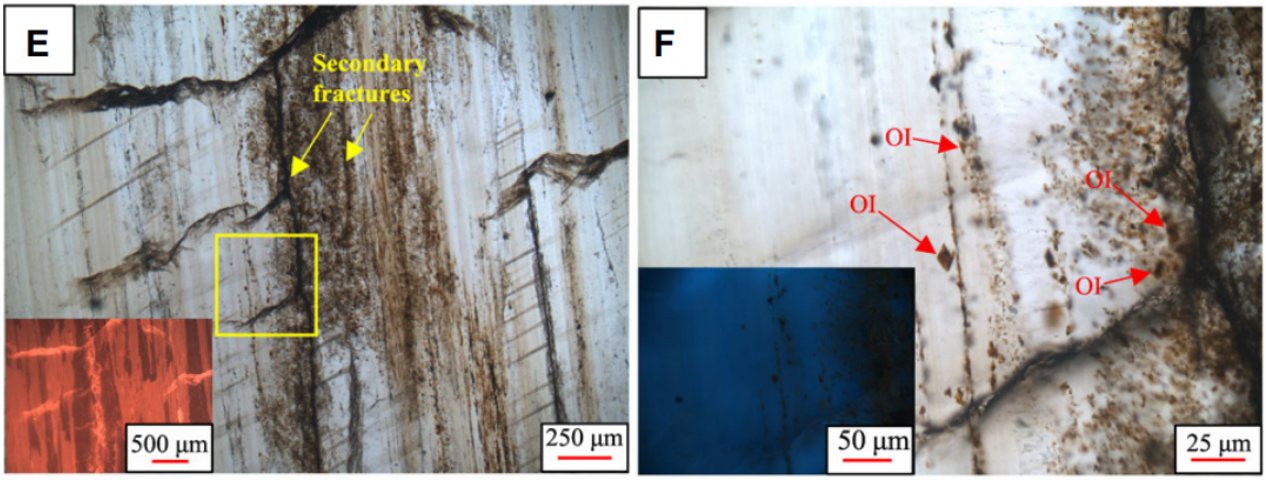

Figure 7
Photomicrographs analysis. A) Cathodoluminescence and B) UV light. Showed abundant fractures trapping nonfluorescent oil inclusions indicating that it was formed at a late stage and the latest stage of oil charge (Ping et al., 2020).

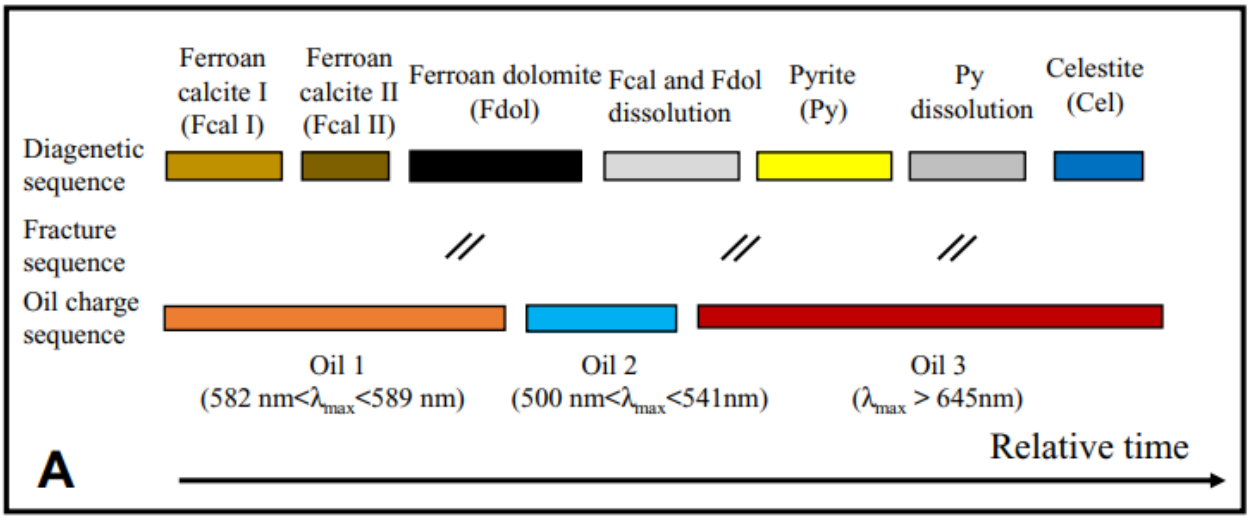

Figure 8
Paragenetic sequence (Ping et al., 2020)

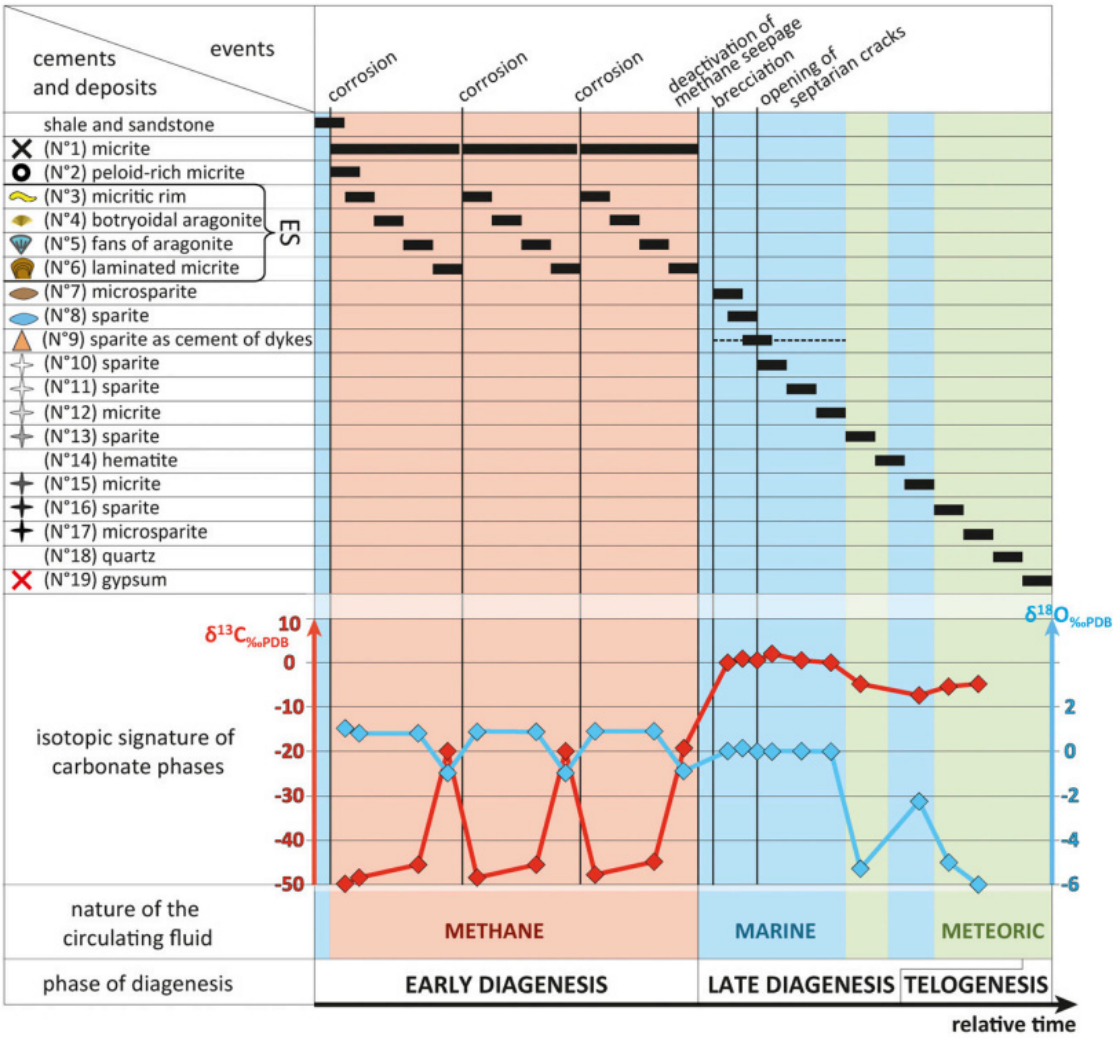

Figure 9
Paragenetic sequence observed in research outcrops (Blouet et al., 2017)

when the diagenetic happened, the oil charge events are through paragenetic sequence, and provable from the result of photographic analysis in figure 6, the oil charge events were divided into 3 stages. The oil 1 charge event trapped in ferrous calcite with a similar wavelength than the next stage oil inclusions trapped in late ferrous dolomite meaning that more mature oil charge happened are grouped as oil 2 charge, the last stage is oil inclusions that primarily trapped in secondary fractures that cut through ferrous calcite and dolomite crystals this suggesting that oil 3 charge happened (Figure 7 and Figure 8) (Ping et al., 2020). Paragenetic sequence was also mentioned in a published paper written by Blouet et al in 2017, studying about biogenic gas mechanism produced by a seep carbonate paragenesis in Panoche Hills, California. The author, Blouet identified from the two outcrops analyzed located in the Moreno Formational and Cima Sandstone lentils found that there is a recurrent paragenetic sequence that could be used to evaluate the paleo fluid flow in the area. The paragenetic sequence was grouped into two stages of diagenetic, which are early and late. From the thin section analysis, Blouet et al interpreted that the seepage process from the paragenetic sequence was started by Authigenic carbonate precipitation inside a burrow that acted as a pathway for the hydrocarbon flow then coated by micrite from the mixture of methane with the surrounding sediments. From the preservation of the micrite, shows that the carbonate is deposited at a shallow depth before the compaction occurs. From Figure 8 there is a three cyclic fluid flow sequence or elementary sequence of micritic rim, botryoidal aragonite, fans of aragonite, and laminated micrite, thus indicating the early stage of diagenesis. Moving to the next stage which is the late diagenesis was showed by a formation of microsparite as an in-situ replacement of the earlier

micrite, at this stage there is also a shift in the isotope number from the methane-derived carbonate into the marine carbonate signature. There are also a few changes from marine to meteoric fluids that can be seen from the isotropic trend. So, the three kinds of diagenetic fluids that could reviewer be diverse to methane, marine, and meteoric waters. The sequence event that happened during late diagenesis started with the first marine cement formation of sparite, micrite, hematite, microsparite, quartz, and ends as gypsum precipitation indicating a telogenesis stage (Figure 9 and 10) (Blouet et al., 2017).

Another publication from (Rosales et al., 2018) discusses Microfacies, diagenesis, and oil emplacement of the Upper Jurassic Arab-D carbonate reservoir in an oil field in central Saudi Arabia (Khurais Complex) also using paragenetic sequence to study the productivity of the reservoir. The result of the paragenetic sequence is obtained from a few analyses such as petrographic of microfacies, mineralogy, neomorphism or replacement, and the relationship between porosity and cementation. The study is accomplished by combining observations using petrographical, epifluorescence (UVF), and cathodoluminescence (CL) microscopes. The diagenetic and paragenetic study indicate a sequence that includes three events of dissolution, four stages of calcite cement, and two last stages of dolomite formation that involve the 5 dolomite zones. From the result of UVF (fluorescence), the presence of oil is trapped in various carbonate cements suggesting that there are about two phases of oil charging (Figure 11) (Rosales et al., 2018). VOSviewer analysis also can be used to determine the bibliometric map with the author of the article which showed the range of impact from each article, the maximum numbers parameter set to 25 and from 37,848 authors only 537 authors meet the threshold and were grouped into 8 clusters with different colors that indicating each cluster. The red Clusters have the most cited authors with 133 authors and the smallest group of nodes is cluster 8-colored brownish gray with 13 authors. (Figure 12).

This analysis of Co-citation from the country, which the articles were from, is grouped into nine clusters with different colors and there are 46 countries in total. The biggest node group is cluster one with red nodes which has nine countries, and the smallest group of nodes is cluster nine with a brownish-gray color and has around 2 countries, which are India and Denmark. Indonesia is in cluster two (blue) with six countries such as Ireland, Japan, Malaysia, Singapore, Sweden, Switzerland, and the United Kingdom. From this map, we can also see the line on each node that represents the connection between countries, the bigger the node shows that the country has made many contributions and publications in the paragenesis world and if we look closely at the Indonesia node, it shows that Indonesia had a close relation to some country which is United Kingdom, France, Sweden, and Iran but Indonesia represented by a small node which means that Indonesia still have a little publications in the paragenesis study (Figure 13).

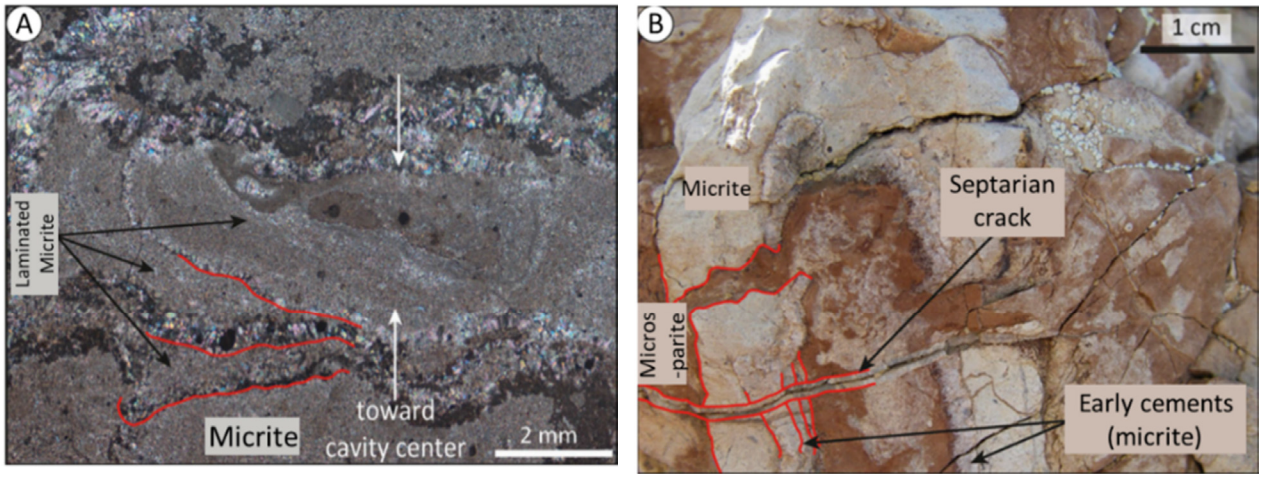

Figure 10
Result of the petrographic analysis from the minerals. A) Elementary sequence laminated micrite indicates the early diagenesis stage. B) Late diagenetic minerals, burrow-coated micrite cross-cut by crack-filled microsparite and later by a septarian crack (Blouet et al., 2017)

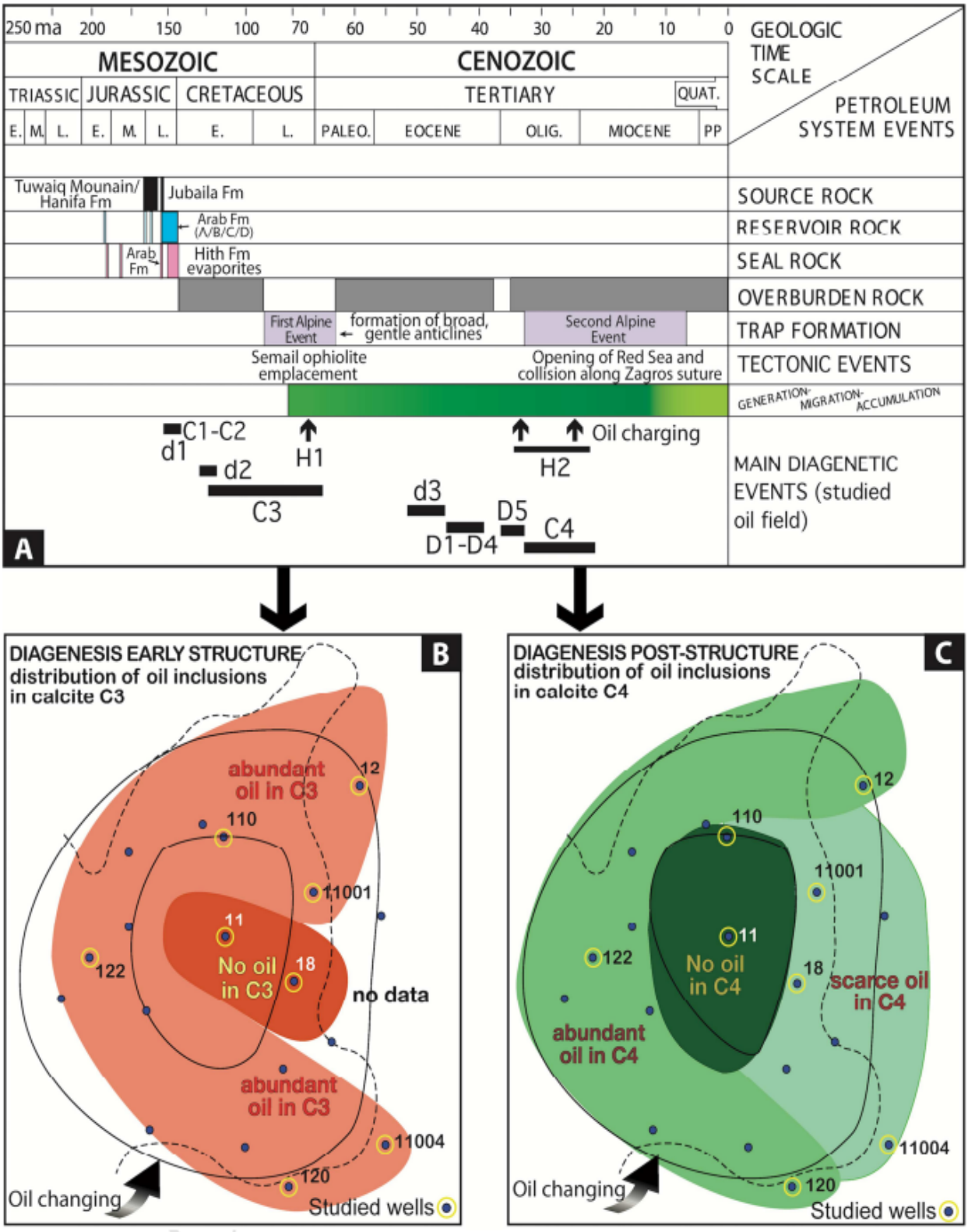

Figure 11
Paragenetic sequence of diagenetic events against time for the Arab-D study oil field. There are two phase of oil charging (H1-H2) that occurred in late Cretaceous (H1) and Oligocene (H2) (Rosales et al., 2018).

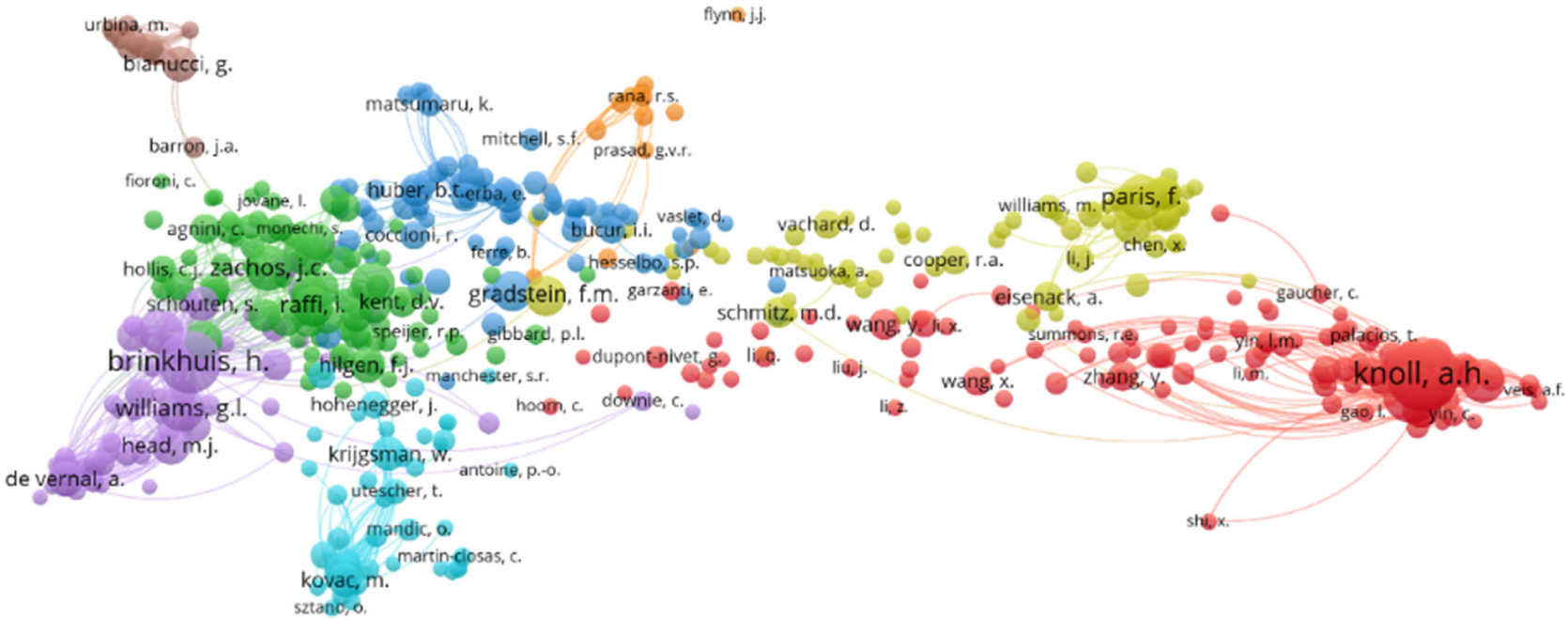

Figure 12
Co-citation bibliometric map of the cited author

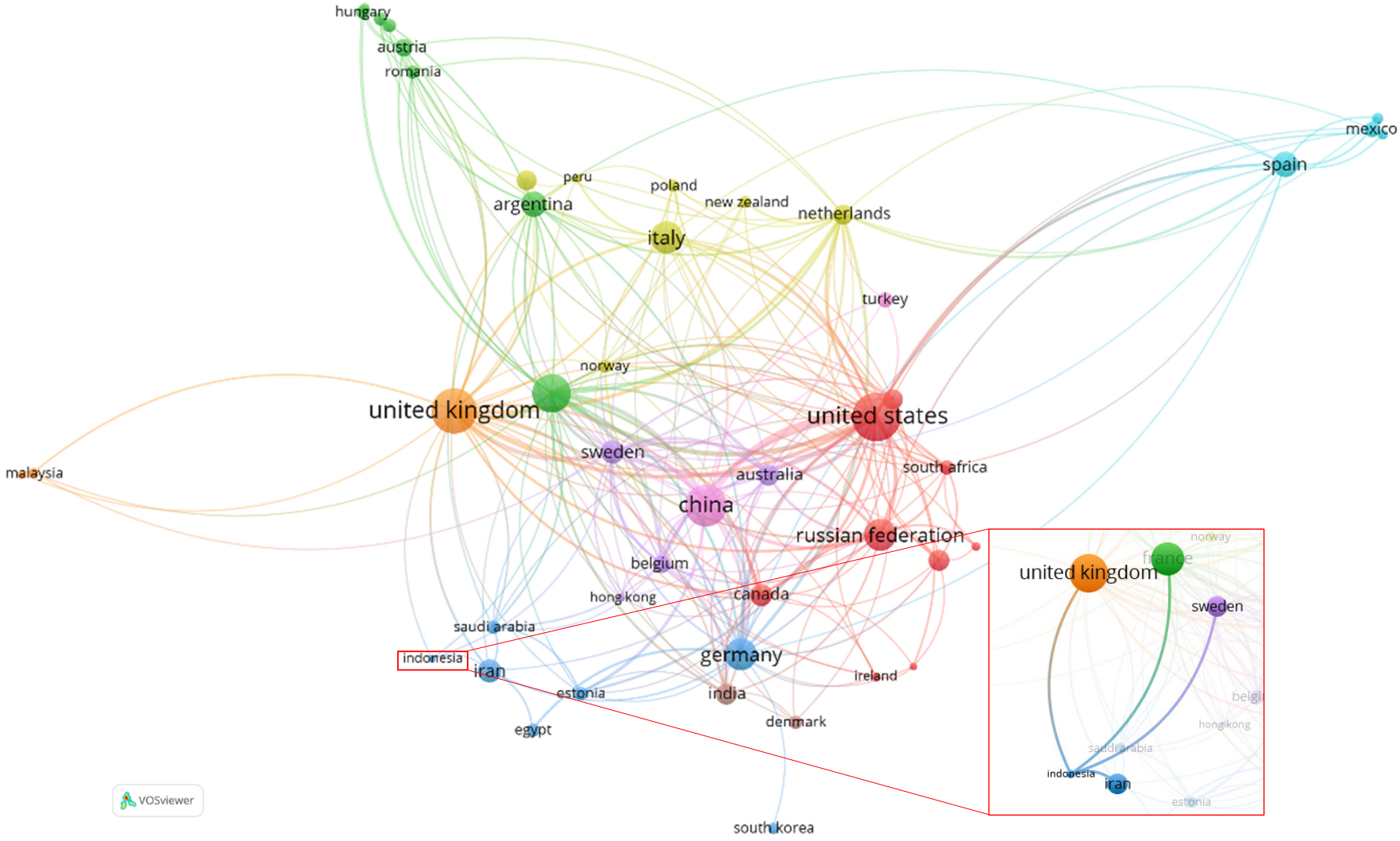

Figure 13
Co-citation bibliometric map from network of countries

CONCLUSIONS

This Article shows the overall summary about carbonate paragenesis obtained from secondary data, which is a few articles published years before. Graphic from distribution of publications in paragenesis showed a stable and increasing trend line that indicates a consistent publication and study about this topic. A few bibliometric, analyses that were done resulted in a few bibliometric maps, which are a Co-occurrence bibliometric map of author keywords, a Co-citation bibliometric map of the cited author, and a Co-citation bibliometric map from the network of countries. Paragenesis study especially paragenetic sequence is very connected to many study fields. There are about 987 articles published on the topic of paragenesis from 1999 until 2022 with 537 authors from 46 different countries. The statistical analysis that was done according to the secondary data resulted in a consistent trend line that is overall increasing even if there is a drop in some years, but the graphic line keeps on increasing.

This bibliographic analysis can also show the correlation between each keyword in the co-occurrence map of keywords showing topics related to paragenesis, especially paragenetic sequence. The map showed that paragenetic sequence connected to a few other keywords such as Formation, Stage, fracture, mineralogy, deposit, phase, process, and many other keywords. Another thing is that bibliometric analysis also can determine the mapping of the author's co-citation analysis of each publication and from the country it originates from and is divided into nine clusters with the biggest node, which is the United States, United Kingdom, China, and Russia. Meanwhile, Indonesia is in cluster two and mostly related to some countries such as the United Kingdom, France, Sweden, and Iran.

Based on the explanation above shows that paragenesis is an important subject to continue studying and researching. Paragenesis and diagenesis not only need to be studied in the ore deposits field, but they also need to be used in the oil and gas fields, especially to determine when the oil or hydrocarbon is placed inside the pores and also from paragenesis we can know for sure about the geological history from the mineral deposits, formed fractures, compactions, and others products formed because of the diagenesis burials. Paragenesis also growing in many countries, especially in Indonesia, which is, still little publication but has promising growth. Therefore, the paragenesis study needs to be improved and much discussed because the future of paragenesis is still wide and promising.

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GLOSSARY OF TERMS

Symbol	Definition
Bibliometric	is a set of methods to quantitatively analyze scientific and technological literature.
Carbonate	is a salt of carbonic acid, characterized by the presence of the carbonate ion, CO_2^{-3}.
Diagenesis	is changes in sediment or sedimentary rocks during and after rock formation, at temperatures and pressures less than that required for the formation of metamorphic rocks or melting. It does not include changes from weathering.
Hydrocarbon	is an organic compound consisting entirely of hydrogen and carbon.
OpenRefine	is an open-source desktop application for data cleanup and transformation to other formats, commonly known as data wrangling. Similar to spreadsheet applications and can handle spreadsheet file formats such as CSV, but it behaves more like a database.
Paragenesis	is a petrologic concept meaning an equilibrium sequence of mineral phases.
VOS viewer	is a software tool for constructing and visualizing bibliometric networks including journals, researchers, or individuals.

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