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Particle Migration in Hydrocarbon Reservoirs During Production: Problems and Trigger Factors

Naomi A. Ogolo and Mike O. Onyekonwu*

Institute of Petroleum Studies, University of Port Harcourt, Rivers State, Nigeria

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Abstract

One of the many challenges facing the petroleum industry during oil and gas production is particle migration from reservoirs to surface facilities. Hydrocarbon formation particles that disintegrate, detach and migrate from reservoir rocks to production facilities during oil and gas production give rise to a number of problems. These problems are discussed in this paper and the factors that trigger particle migrations are highlighted. The difficulties associated with controlling the factors that trigger particle migration are reviewed. Most of these factors cannot be controlled either because they are essential to ensure and enhance oil and gas production which is the primary target of the petroleum industry or because they are natural phenomena. The origin of particle migration problem and reasons for formation unconsolidation are considered from a geological point of view. Managing particle migration by the most efficient means or adopting a preventive technology that will prevent particle dislodgement during oil and gas production is recommended.

***Keywords**: Particles; Migration; Unconsolidation; Rock; Formation.*

1. Introduction

Formation particle migration during hydrocarbon production is one of the oldest problems posing a big challenge to the oil and gas industry. It is a worldwide problem facing petroleum producing operators and one of the toughest to solve. In fact, some reservoirs can produce several tones of fines and sand annually. Sand and fines management techniques have been developed, modified and improved upon over the years, but a complete solution to the problem has been elusive.

Production of fine particles from reservoir rocks during oil and gas production result from disintegration of the formation and detachment of formation particles from their parent rock. This is a phenomenon peculiar to unconsolidated formations. The loosened particles migrate along in flowing fluids through reservoir pores into wells, production lines and surface facilities where their presence and impact create problems during production. Hence, the goal in this paper is to review the problems caused by migrating particles in reservoirs during hydrocarbon production and to highlight the trigger factors. Geologically, the origin of particle migration problem and possible causes of formation unconsolidation are discussed.

1.1. Problems caused by migrating formation particles

Fines migration during hydrocarbon production is a serious matter in the oil and gas industry around the world because many hydrocarbon formations are unconsolidated in nature. Evidence of this can be seen from a physical examination of some core samples and plugs obtained from hydrocarbon bearing rocks. In fact, fine particles from producing wells into production and surface facilities give further evidence to this fact. Particles migration, if unattended to can lead to numerous problems; it can ultimately result in production shut down or well workover operations. Consequences of solid particle production include destruction of downhole and surface equipment, downtime and facility replacement costs. These problems which no doubt emphasize the need to adopt a preventive measure are thus reviewed as follows:

Permeability impairment: Some formation particles such as sand grains can block tiny pore throats of pore chambers in reservoirs when they are stuck because some of these tiny particles are larger than some pore throats. When this happens, flow paths of fluids in porous media are obstructed and permeability is adversely affected. Swelling clays such as Montmorillonite can cause serious permeability problem in formations by blocking pore spaces when in contact with water of low salinity. In the absence of Montmorillonite, loss of permeability has also been observed in sandstone formations caused by clay migration of hexagonal-shaped kaolinite and crystals of needle–shaped mica (a type of Illite) which are non-expandable clays [1-2]. Accumulation of fine particles near wellbores causes flow obstructions which can lead to severe formation damage and production impairments.

Wellbore instability: Particle dislodgement and migration in formations can cause serious erosion of near wellbore formations. This can result in wellbore instability and can undermine well integrity if prompt corrective measures are not taken. In extreme cases, casing collapse can occur when the formation sands surrounding the casing have been washed away, creating cavities behind casing walls.

Hindrance to flow assurance: Migrating formation particles that succeed to penetrate through screens at perforated portions of wells also create problems during production operations. Migrating fine particles promote scale formation in wells and production lines. Deposited migrating particles on production facilities reduce well productivity indices and flow capacity which hinders flow assurance.

Damage to production facilities: Formation sand particles erode production screens placed around perforated portions of casings by regular sand blasts, thereby destroying the screens. Sand intrusions into pieces of production equipment cause damage to valves, chokes, pumps, separators and pipelines that are designed to carry only fluids, not solid particles. Reduction of surface storage capacity for petroleum fluids by sand accumulation is also a problem, unless the sand can be separated from the fluid before storage.

Downtime and financial losses: Loss of production time and the cost of regular sand cleaning operations have financial implications because it increases the cost of hydrocarbon production. Other indirect financial losses resulting from periods of downtime related to particle migration include scale removal, replacement of damaged production facilities and formation damage cleanup operations.

Environmental issues: Disposal of produced solid formation particles from hydrocarbon reservoirs constitutes an environmental concern. This is because produced sand and fine particles contain radioactive elements and heavy metals just like the formation water surrounding them. This has attracted strict disposal regulations to ensure environmental safety, thus making disposal of produced fines and sands expensive. Creation of cavities in the formation by solid particle removal could result in rearrangement of the formation structure to fill up the created voids. Such solid particle adjustments can result in subsidence on the earth's surface after many years of formation particle removal. This kind of environmental degradation is a heavy price to pay and is a long term environmental consequence that should be guarded against.

2. Origin of the problem

Fines are tiny grains of sand, silt and clay particles that disintegrate from the rock matrix. Hydrocarbon reservoir formations are made of compacted sand grains, silt, clay and minerals that contain fluids such as formation water, oil and gas. These formations are porous and permeable and can be consolidated or unconsolidated. For unconsolidated formations, disintegrated sand grains and very tiny particles (especially clays) called fines become loose and as such are easily carried by flowing fluids from their point of detachment through reservoir pores into production and surface facilities. Unconsolidated reservoir formations are therefore the source of infinite generation of fine particles during oil and gas production. Unconsolidated formations tend to be more permeable than consolidated rocks. During production, the unconsolidated formation enhances fluid flow but also has the capacity to carry along in the flow loose formation particles which constitute the problem under consideration. A geological insight into this problem reveals factors responsible for unconsolidation in formations.

2.1. A geological overview

Geologically, any process through which loose or raw sediments are hardened or turned into consolidated sedimentary rock is called lithification. Lithification occurs through compaction, re-crystallization, cementation or a combination of these processes. Causes of unconsolidation in formations include lack of compaction, lack of cementing agents, non-occurrence of re-crystallization and age of the rock. Formation unconsolidation can also occur as a result of a combination of these factors.

Lack of compaction: Compaction means squashing or compressing loose sediments together. Compaction in formations is a natural phenomenon that occurs as a result of overburden pressure, and it can aid formation consolidation. However, compaction alone may not be enough to initiate rock consolidation. This is because some formations that are deeply buried, well compacted and under high pressures are still unconsolidated, while some shallow formations under moderate pressures have a degree of consolidation. In as much as pressure and compaction are essential in solidifying rocks, there seems to be a chemical factor that tends to enhance consolidation in formations. Re-crystallization or cementing minerals must be responsible for consolidation of formations.

Non occurrence of re-crystallization: Re-crystallization involves precipitation of such materials like calcium and silica to produce interlocking textures. The absence of these processes and their minerals could account for unconsolidation in some reservoir formations. Re-crystallization may or may not take place in formations because it depends on the type of reservoir rock. Re-crystallization mainly occurs in carbonaceous rocks, not in sandstone formations.

Lack of cementing materials: Formation in-situ strength is derived mainly from the natural cementing materials. Cementation occurs when there are cementing materials in the formation that binds sediments together. Cementation glues raw sediments together by oxidation of some compounds such as calcite, aluminum, silica and iron oxides. Cements form in sediments when sea or formation water containing cementing minerals travels through pore spaces in the formation.

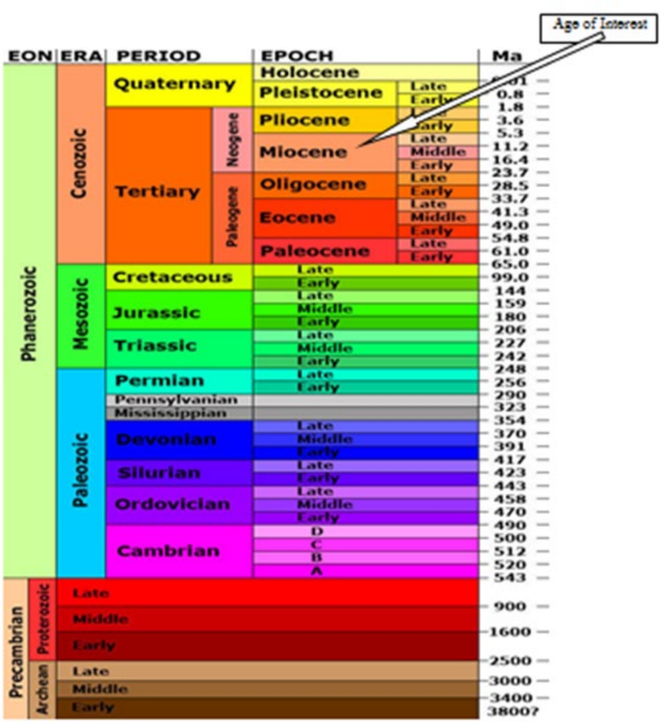

Figure 1. The geologic time scale

Mineral crystals form in-between sediments and as a result bind loose formation particles together. Minerals like calcite, quartz and hematite form cementing agents in sedimentary rocks and they include calcium precipitate, silica oxide, magnesium oxide and iron oxide. Therefore, lack of cementing materials in some great depth sandstone reservoir formations must be responsible for unconsolidation of some reservoir formations. When the cement bonding agents in a formation is destabilized, it can lead to detachments of particles from the rock's skeleton structure. Destabilization of bonding properties in a formation can be caused by drag forces from high fluid flow rates, dissolution and erosion of cementing materials in the rock by water and breakthrough of water or gases.

Age of the rock: Another likely natural cause of formation unconsolidation is the age of the rock. It has been observed from many studies that Miocene age and younger formations are more unconsolidated than older formations [3]. The reason for unconsolidation of formations belonging to the Miocene age could probably be attributed to the young nature of these formations, perhaps given some millions of years, these formations might become consolidated. The geologic time scale is shown in Figure 1 and Miocene age formations can be seen to be quite young in comparison to many other formations.

3. Factors that trigger particle migration in reservoirs

The fact that a formation is unconsolidated does not mean that particles must migrate. There are factors that trigger particle migration in reservoirs and two major factors are high production rates and water production. Other factors include formation wettability, pressure depletion, high viscosity crude, formation weakness, fatigue and injected fluids. If these factors can be controlled, then particle migration will not occur or its occurrence will be minimal. Unfortunately, little or nothing can be done about most of these factors because some of them are tied to economics while others are essential for hydrocarbon recovery and production maintenance.

High Production Flow Rate: High production rate of fluids from reservoirs is a major factor that induces particle migration. Production of fines and sand during oil and gas exploitation occur when induced in-situ stresses exceed the formation in-situ strength [4]. There is a critical flow rate beyond which the hydrodynamic force exceeds the binding forces holding the formation particles together. When this in-situ cohesive binding force is exceeded, fines dislodge from their matrix structure and start migrating with the flowing fluids. It has been shown experimentally that particle migration can be controlled by reducing flow rates. Mobilization of quartz fines is mainly triggered by the operational hydrodynamic forces in the formation [6-7] which is dominated by production flow rate. For economic reasons however, it is not feasible to maintain very low rates in production and this makes the option unattractive.

Water Production: Water Production has been discovered to be a primary factor that triggers particle migration in reservoirs. When only oil is produced, little or no particle migration occurs but when water is produced, fines and sand become part of the flow. Because most formation particles are water wet, water breakthrough tends to dislodge, induce and enhance the mobility of these particles. Moreover, water sometimes dissolves and washes away cementing agents in a formation, thereby rendering the rock particles prone to detachment and migration. This is especially so when the water salinity is low because low salinity water destabilizes clays and other particles, and that is why low salinity water is sometimes used to test how effective chemical agents are in controlling migrating particles in formations.

High salinity water does not mobilize clayey fines; in fact clays are undisturbed in the presence of high salinity brine [8] while oil recovery using high salinity water is poor. Several mechanisms through which water destabilizes rocks and dislodges particles from the matrix structure leading to fines and sand production has been investigated and explained [8].

To prevent water production from reservoirs is almost impossible because many reservoirs in the world are under water drive mechanism. Water encroachment especially for reservoirs that have large underlying aquifers is a natural phenomenon that is difficult to control as long as production takes place. Additionally, water aids in pressure maintenance and in expelling oil from reservoir pores, necessitating artificial water injection schemes. Preventing water production during hydrocarbon recovery especially in oil reservoirs in order to control particle migration is not a feasible option. Ironically, low water salinity has been reported to better enhance oil recovery while oil recovery using high water salinity is poor. Thus, it is expected that low salinity water will continuously be injected into oil reservoirs to enhance recovery even though it triggers particle mobilization.

Formation Wettability: Particle migration is partly controlled by wettability. In multiphase flow, particles move only when the wetting phase moves. Most clays and sands are water wet, not oil wet and as such would not move in the non-wetting phase. For this reason, they tend to be mobilized in flowing fluids when water is present. For particles to move in the wetting phase, an adequate saturation of the wetting phase is necessary to achieve a continuous phase that mobilizes the fines. Therefore, water wet particles may be held in place by the immobile connate water saturation until water breakthrough occurs. Wettability and interfacial forces are sometimes altered by injection of water wetting treatment fluids and surfactants. These injected fluids can mobilize fines that were initially held in place by wettability phenomenon.

Pressure Depletion: Pressure depletion is one of the causes of sand production. As pressure decreases, the bonding forces between sand grains are weakened or broken. High reservoir pressures can compact sand grains and prevent dislodgement of formation particles. In the absence of cementing minerals in porous media, a high confining pressure works as a cementing material by pressing and holding the sand grains together. Upon contact, sand grains get attached to each other by cohesion. Unconsolidated sands becomes loose if there is no confining pressure, and at high confining pressures, high flow rates can be achieved without sand production [9]. Therefore, pressure depletion in reservoirs can induce particle migration, and naturally low reservoir pressures can result in formation unconsolidation.

High Viscosity Crude: Viscous crude exhibits a high fluid carrying capacity than light crude. It has been shown that viscous fluids can carry heavier formation particles than light crude and so it promotes fines migration especially at high flow rates. A conducted test shows that when using light crude oil for displacement, fine particles were produced but when heavy crude was used for displacement, the largest given sand sizes were produced. Studies have also shown that controlling only flow rate cannot stop sand production from heavy oil reservoirs [7].

Formation Weakness and Fatigue: Particle migration can be triggered by formation weakness and fatigue effects. Destabilization of bonding properties in a formation which results in weakening the formation can be caused by injected fluids used as treatments such as acids, surfactants and steam. Hydrochloric acid used in well completion adversely affects the strength of formations. High temperature in steam injection has initiated sand production when there was no previous sand production. High temperatures associated with steam flooding can induce clay transformation and physical dissolution of portions of rock matrix thereby releasing encapsulated fines [10].

It has been shown that some surfactants can mobilize fines that were previously held in place by wetting and interfacial forces [11]. High pH value solutions have been used to test the resistance of formations to release the fines they contain because high pH value solutions have the capacity to initiate and mobilize fines in formations. Like high pH solutions, low salinity brine either injected into the formation or from natural water flooding also promotes fines migration by some complex reactions with clay minerals in rock formations. Injection of miscible fluids like CO_2 can lower the cohesion forces by affecting the surface tension of wetting fluids. All of these fluids weaken formations and lead to particle dislodgement, migration and production from reservoirs.

Fatigue effects can be induced by several operations. These include principal stresses, pressure depletion, pressure surges, stimulation processes, sudden start of artificial lift, well shut-ins and bean-ups [12]. Sudden change in flow rates such as change of choke size, intermittent gas lift and uncontrolled flow back after stimulation can also induce formation fatigue and fines migration. Local pressure disturbances caused by multiphase flow keeps fines agitated and reduce their binding integrity. Production flow rate must be changed when necessary to satisfy certain technical and economic requirements such as well testing, cleanup exercises, maintenance and work over operations. This type of change in flow rate can also trigger particle dislodgement and migration in formations. All these technical operations that induce formation weakness and fatigue are important requirements which cannot be avoided because they ensure safe and continuous petroleum production.

4. Difficulties in controlling the trigger factors

It is difficult to control most factors that trigger particle migration in hydrocarbon reservoirs. This is either because the trigger factors are essential to ensure and enhance oil and gas production which is the primary objective of the petroleum industry or because they are natural phenomena. High production flow rate is a primary factor that destabilizes formation particles, but for economic reasons, there is a limit to which flow rate can be reduced hence it is not feasible to maintain very low production flow rates. Pressure depletion in reservoirs can induce particle migration, and naturally low reservoir pressures can result in formation unconsolidation. Unfortunately, one of the characteristics in hydrocarbon reservoirs during production is pressure drop over time, unless a pressure maintenance scheme is initiated or if natural water encroachment recharges the system. Wettability and high temperatures are natural phenomena that are difficult to alter. It is also difficult and expensive to reduce the viscosity of heavy crude in formations in order to facilitate production or militate against particle mobilization.

Water encroachment in petroleum reservoirs is a natural phenomenon that is difficult to control as long as production takes place especially in reservoirs that have large underlying aquifers. Sometimes artificial water injection schemes are initiated because water aids in pressure maintenance and in sweeping residual oil from reservoir pores to production wells. Since oil displacement by water is an efficient oil production strategy, preventing water production during hydrocarbon recovery, especially in oil reservoirs in order to control particle migration is not practical. Fatigue and formation weakening effects induced by necessary technical operations that result in particle dislodgements in reservoirs cannot be avoided. It is therefore clear that most factors that trigger particle migration in reservoirs are difficult to control. If oil and gas must be produced from unconsolidated formations, then fines mobilization problem has to be managed. Alternatively, a technology that can prevent particle dislodgement and migration in reservoirs during hydrocarbon production needs to be deployed.

5. Conclusions

The problems caused by migrating particles in petroleum reservoir formations include permeability impairment, wellbore instability, hindrance to flow assurance, damaging of production facilities, environmental issues, downtime and financial losses. Geologically, formation unconsolidation can occur as a result of one or more of the following factors: non-recrystallization of the formation minerals, lack of compaction of the formation, lack of cementing materials in the rock and the young age of some reservoir rocks.

Factors that trigger particle migration in reservoirs include pressure depletion, high flow rates, wettability, high oil viscosity, high temperatures, water production, water salinity, formation weakness and fatigue due to certain production operations.

Most factors that trigger particle migration are difficult to control because some are tied to economics, some are natural phenomena while others are necessary for efficient and safe production of petroleum.

Recommendations

One viable option in oil and gas production from unconsolidated formations that produce particles is to manage the problem by the most efficient means.

Another option is to search for and deploy a technology that will prevent formation particle dislodgement from the rock matrix during production, and that will not jeopardize hydrocarbon recovery efficiency.

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To whom correspondence should be addressed: Dr. Naomi A. Ogolo, Institute of Petroleum Studies, University of Port Harcourt, Rivers State, Nigeria; E-mail: amoniogolo@yahoo.com